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Integrated hydrogen production options based on renewable and nuclear energy sources

Mehmet F. Orhan [a,*], Ibrahim Dincer [b], Marc A. Rosen [b], Mehmet Kanoglu [c,1]

[a] Department of Mechanical Engineering, American University of Sharjah, P.O. Box 26666, Sharjah, United Arab Emirates
[b] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, Canada L1H 7K4
[c] Department of Mechanical Engineering, University of Gaziantep, 27310 Gaziantep, Turkey

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ABSTRACT

Due to varied global challenges, potential energy solutions are needed to reduce environmental impact and improve sustainability. Many of the renewable energy resources are of limited applicability due to their reliability, quality, quantity, and density. Thus, the need remains for additional sustainable and reliable energy sources that are sufficient for large-scale energy supply to complement and/or back up renewable energy sources. Nuclear energy has the potential to contribute a significant share of energy supply with very limited impacts to global climate change. Hydrogen production via thermochemical water decomposition is a potential process for direct utilization of nuclear thermal energy. Nuclear hydrogen and power systems can complement renewable energy sources by enabling them to meet a larger extent of global energy demand by providing energy when the wind does not blow, the sun does not shine, and geothermal and hydropower energies are not available. Thermochemical water splitting with a copper–chlorine (Cu–Cl) cycle could be linked with nuclear and selected renewable energy sources to decompose water into its constituents, oxygen and hydrogen, through intermediate copper and chlorine compounds. In this study, we present an integrated system approach to couple nuclear and renewable energy systems for hydrogen production. In this regard, nuclear and renewable energy systems are reviewed to establish some appropriate integrated system options for hydrogen production by a thermochemical cycle such as Cu–Cl cycle. Several possible applications involving nuclear independent and nuclear assisted renewable hydrogen production are proposed and discussed. Some of the considered options include storage of hydrogen and its conversion to electricity by fuel cells when needed.

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* Corresponding author.
E-mail addresses: morhan@aus.edu (M.F. Orhan), ibrahim.dincer@uoit.ca (I. Dincer), marc.rosen@uoit.ca (M.A. Rosen), kanoglu@gantep.edu.tr (M. Kanoglu).
[1] Visiting professor at American University of Sharjah during 2010–2012.

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1. Introduction

In today's world, energy and its transformation play critical roles in our lives and have a direct impact on every sector of the economy affecting the overall economic and societal well-being. Generally, economic and human health relates to per capita energy consumption. Energy is used in almost every human activity. Areas where energy is used include transportation, household work, agriculture, industry and manufacturing, service, buildings, and more. Thus, energy is consumed both directly by us in transportation and for household purposes, as well as indirectly by consuming goods that require energy in their production, delivery and preservation. Fossil fuels such as coal, oil and natural gas satisfy over 85% of our energy needs [3]. Combustion process, which transforms the fuel's chemical energy into other forms of useful energy in internal combustion engines, steam and gas turbines, boilers and like, plays a major role in the consumption of these fossil fuels. These combustion-based processes, however, produce pollutants (e.g., nitrogen oxides, carbon monoxide, hydrocarbons) and greenhouse gases (e.g., carbon dioxide). In addition, only about 30% of the fuel's chemical energy is transformed into power by some of these power generation systems. Therefore, there is an urgent need for alternative energy conversion methods.

The increase in recorded average temperatures over the globe since the mid-20th century is mostly attributed to the observed increase in the anthropogenic greenhouse gas concentrations. Greenhouse gases (GHGs) such as carbon dioxide, water vapor and methane, absorb solar radiation and hence create a natural greenhouse blanket effect around the Earth. Without this effect, temperatures would be lower [8]. Carbon dioxide is a lasting greenhouse gas. It can remain for hundreds of years once it is added to the atmosphere. Human activities have been the significant contributor to the atmospheric concentrations of all major GHGs that have increased considerably since pre-industrial times. For example, carbon dioxide concentrations have risen by over one third from 280 ppm (ppm) in around 1750, to 379 ppm in 2005. It has been stated that CO_2 levels could reach 550 ppm by 2050, leading to warming by at least 2 °C [8]. Some effects of global warming are the rise of sea levels, glacial retreat, species extinction, an increase in the ranges of infectious diseases and an increased likelihood of severe weather patterns. For example, a temperature rise of just 2.7 °C could lead to the melting of the Greenland ice cap [8]. Therefore, governments and corporations have started taking actions to restrain global warming and its effects.

Major global concerns such as over-population, air pollution, fresh water pollution, coastal pollution, deforestation, biodiversity loss, and global climate deterioration further influence energy development. These growing concerns about global warming have revitalized R&D in efficiency improvement, alternative energy sources and in methods to decrease CO_2 emission. The interest in energy has received another important boost in recent years. This interest was primarily driven by the non-linear rising of energy consumption by the highly populated countries, and accompanied by the heightening tensions with many of the oil and gas producing nations. Any large-scale energy-related activities should be engaged in ensuring their sustainability to prevent catastrophic global consequences. While having various definitions, sustainable development refers to activities that meet the current needs without destroying the ability of future generations to meet theirs, with a balance among economic, social, and environmental needs [4].

Quantitative sustainability criteria need to be established to make any activity sustainable. For example, in the energy sector these criteria go well beyond the conventional thermodynamic and economic indicators such as production, consumption and conversion efficiencies and costs. Sustainability criteria must also include both short term and long term social, political, and ecological considerations. However, those are typically very difficult to quantify and their application performance depends on the country, and even the community, to which they are to be applied. The planning and design of sustainable systems is further complicated than conventional planning and design that does not include the rigorous investigation of sustainable approaches. This complexity is caused by the addition of many interdisciplinary and probabilistic multi-objective sustainability criteria that are added to the generally deterministic process of system modeling, analysis, optimization, and selection [18].

The rise in concentration of greenhouse gases in the atmosphere should be slowed down to keep the threatening dynamics of climate change within the human scope of control. The impact on the environment has been described as the product of population, affluence and technology [29]. Thus, the energy use trends should be reduced by more well-judged consumption. This can be done through measures such as higher energy conversion efficiency, reduction of waste, and more modest lifestyles [18]. These measures offer the highest impact on the reduction of fuels and materials consumption, and hence on the associated undesirable emissions, and environmental and political consequences. However, application of these measures is not easy, since the barriers facing energy efficiency and renewables are stubborn, interconnected, and deeply embedded in the social fabric. The main cultural and behavioral barriers are misunderstanding about electricity and energy efficiency, expectations about cheap and abundant forms of electricity supply,

and a strong personal desire among consumers to prioritize comfort, control and freedom rather than sustainability. To overcome these interrelated impediments, equally conscientious policies are required. Other obstacles include political and regulatory barriers; inconsistent government standards and uneven policymaking; underfunded research and development; and an overbearing approach to research projects [27]. Also, financial and market impediments include the lack of readily available information on energy efficiency and renewable electricity to both users and producers; improper discount rates and unacceptably high rates of return for energy investments; the principal-agent problem; the invisibility of energy savings; predatory practices undertaken by some energy firms and electric utilities; and a desire for businesses and industries to stick to their core missions rather than invest in different forms of energy supply. Finally, esthetic and environmental challenges include improperly assessing negative externalities; esthetic values; the symbolic nature of energy efficiency and renewable energy; and internal fighting among renewable power advocates. Pricing electricity accurately, implementing a national Feed-In-Tariff (FIT), and undertaking forms of wealth reorganization to fund education programs, protect the poor, and provide money for energy efficiency projects are crucial methods among many policy mechanisms to promote renewable energy and energy efficiency [27].

Sources and solutions compete in ever changing positions and conditions in the history of the energy sector since World War II. Even though the overall dominance of coal at the beginning of the period has ended, it still remains as a significant source in the generation of power today. Nuclear energy has succeeded in taking over from coal for only a few countries such as France and Belgium. Despite their exhaustible and premium fuel character, oil and natural gas cover important share of power generation. None of the distributed generation by on-site combined heat and power units and renewable energy has taken over from centralized systems. The data in Table 1 clearly indicates why fossil fuels have conquered such a large market share in overall energy supplies and power sector. Even in a "low" carbon emission future, fossil fuels can be resilient enough to maintain their strong role. For example, natural gas and premium oil resources will be too valuable to be given up and coal will most likely concentrate on bulk technologies by sequestering the CO_2 in the emissions [29].

In virtue whereof, the energy industries face two sustainability challenges: the need to avoid global climate change and the need to replace traditional crude oil as the basis of our global energy. The challenges will require radical changes in our energy system and utilization. These challenges may require tight coupling of different energy sources such as nuclear and renewable to produce hydrogen for transportation, match electricity production to electricity demand, and meet other energy needs. This implies a paradigm shift in which different energy sources are integrated together, rather than being considered separate entities that compete. Several examples of combined energy systems are described in this study. A novel integrated system approach to couple nuclear and renewable energy systems is presented for hydrogen production by a Cu–Cl thermochemical cycle. In this regard, nuclear and renewable energy systems are reviewed to investigate some appropriate integrated system options for hydrogen production. Several possible applications including nuclear independent and nuclear assisted renewable hydrogen generation are proposed and discussed.

2. Renewable energy sources

Renewable energy sources have been utilized by mankind for sailing ships, waterwheels, windmills etc., since times immemorial. These energy sources span a wide range of technologies and diverse sources such as hydro, wind, solar, tidal, biomass, and geothermal. Although renewable energy sources are vastly available, they need feasible technologies to ultimately serve the mankind. For example, although massive quantities of solar energy are delivered to earth for free, an economic and efficient technology is yet to be offered to convert this energy into useful electricity for an ultimate use.

Renewable energy sources can conveniently be divided into two main groups: intermittent and non-intermittent. The most common intermittent renewable energies are wind and solar while non-intermittent ones are hydro, biomass, and geothermal. Currently, renewable sources provide only about 3% of the world's primary energy consumption, with only about 1% from geothermal, wind, and solar; however their use is growing rapidly. These renewables are mainly used to produce 18% of global electricity demand, with 90% of this electricity being generated by hydroelectric plants [18].

Despite their sustainable appeal and zero or low carbon intensity, renewable energy has a few attributes that smoothly

Table 1
Characteristics of three main energy sources.
Source: Verbruggen [29].

Properties	Nuclear	Fossil fuels	Renewable sources
Energy density	Very dense ($E=mc^2$)	Dense	Mostly diffuse
Scale	Centralized, large scale	Divisible, all scale	Mostly distributed
Control (modulation)	Inflexible, full load	At command	Intermittent, nonpredictable
Compatible with sustainable options	Bulky; intolerant; growth oriented	Sunk costs; expansive investments	Wind and solar need ancillary capacity; hydro/bio independent
Social cost of supply	Very high when all risks are fully incorporated	Very high when all penalties are fully incorporated	Expensive
Market prices	Moderate because risks are not included	Low because externality and penalty costs are not included	High because no risks and externalities are rolled off
Technology	Fusion as backstop? Other technological break throughs deem	Wide diversity with innovations; carbon capture and storage	Surf on inventions and innovations like micro-electronics, new materials, nanotech, etc.
Acute operational risks	High: nuclear accidents; radioactive releases; weapons proliferation; noninsurable	Manageable although severe accidents can happen (mines, tankers, pipelines)	Tiny and distributed; large-scale hydro dams imply high local risks
Chronic pressures	Nuclear waste; inert gas emissions; landscape: more high-voltage lines	CO_2 emissions; air pollution; leakages; solid waste	Landscape and land-use impact (mainly hydro/bio)
Sustainability	Critical (will fusion deliver? and if yes: how?)	Climate change; exhaustion of premium sources	Global and eternal

fit in the business-as-usual energy structures and habits. Most of the available renewable energy sources do not deliver at command but are intermittent. Moreover, they are not centralized but distributed, they are not concentrated but diffused, and they are not cheap to mine but expensive to collect. As it stands now, they are technically and economically unresponsive to the demand of energy-intensive practices of the industrialized and industrializing societies. However, the future can be different from what is today. Wind and solar power generation are, for example, experiencing an exponential growth as costs decrease, and are becoming commercially competitive.

Renewable energy sources are perhaps the only candidate for satisfying most of the criteria of the sustainable backstop supply technology (Table 2). Cost-wise however, it is still more expensive when compared to the present low prices of fossil and nuclear power. For example, photovoltaic power from the sunlight is unlimited as long as the Earth revolves around the sun, yet it is expensive to collect and convert, and then to bridge intermittent supplies. Similar setbacks are being experienced by other renewable energy resources such as wave, tidal, wind, small hydro and biomass. However, not all renewable energy sources have advantage of being unlimited. Some concentrated subclasses of renewable sources, like hydro and biomass, are limited in supply, and their use is competitive to other commercial energy sources. The current unlimited sources are provided via the sun through light, heat, and wind. These forms of energy flows are known to be diffuse, fluctuating, intermittent, and partially unpredictable. Therefore, the collection and conversion of these flows require significant investment, which is mostly needed as the flows are not available at command, need feed-forward control, storage facilities, and make-up. Moreover, the need for back-up power supplies, when the renewables are not available, is another challenge.

Most of renewable options in power sector struggle with high total system costs. The extra prices of constructing, placing and operating renewable energy installations are the main reasons for them to be phased-out by cheaply priced fossil fuels. In addition, when renewable sources address the ancillary services in a continuous supply of power, the price of the average kWh delivered by a full renewable system will also remain at the higher end. Therefore, the renewable economy will be clean but not as cheap as the current prices, although some studies suggest more optimistic futures [29].

Wind power generation, as mentioned earlier, is being deployed rapidly and massively, but limited to regions where it is economically available, and limited by the extent and quality of the electricity distribution grid. For example, it had a capacity increase of about 15 GW electricity in 2006 and forecasted to rise to 29 GW/year by the year 2014 [18]. The main barriers limiting or emerging for the future development of large deployment of wind power are as follows: (i) technology, in which it was found that the rate of annual cost reduction due to improved design, construction, and operation is 15–20%; (ii) market incentives allocated by government for replacing unsustainable and polluting power sources by wind energy; (iii) efficiency of the electricity market and grid, primarily to accommodate the fact that wind energy is intermittent and distributed; and (iv) planning and environmental impact (noise, visual, and wildlife). However, with the development of new units, modifications in existing ones, and improved knowledge of plant sitting; some of the oppositions, such as noise and wildlife impact, are considered to become relatively negligible. In contrast to barriers stated above, wind power systems are increasingly efficient, reliable, and large, with 5 MW turbines reaching a diameter of 125 m and height of 90 m or higher [18]. Moreover, there is a great interest in developing offshore units.

Solar processes can be divided into heating, process heat, and solar thermal and photovoltaic (PV) power generation. PV power generation is becoming the main process for utilizing solar energy as it continues to increase in efficiency and decrease in price, and is employed in many applications. For example, about 5000 MW of PV power has been installed nowadays, and it experiences an exponential growth; 31% a year on an average over the past decade. Multicrystalline silicone is still the dominant PV cell material, with an average efficiency of 15% [18].

Table 2
Evaluation of renewable electricity sources on the criteria of sustainable backstop supply technology.
Source: Modified from Verbruggen [29].

Criteria	Renewable electricity sources performance
Limitation	Renewable energy supplies are global and eternal when derived directly from the available natural flows (solar radiation, light, wind, currents). Hydro and biomass sources for electricity supply are more limited mainly because of competition with other ends (nature conservation, water supply, food production, preserving living areas, conversion to transport fuels, etc.). Because renewable energy can be deployed economically only in an energy economy that is a few times more efficient than the present one, the unlimited character is strengthened.
Decision	More than half of the renewable electricity generation is to be developed in a distributed way. A large part of this can be invested and owned by end-users or by cooperatives of end-users. The power of centralized units will decrease, and so will the nuclear secrecy. The basic principles of procedural fairness are respected.
Accessibility	Renewable energy is available all over the globe. Some regions have more sources while other regions have less sources. The scale, complexity, diversity, security, safety, of renewable energy technologies make them accessible for all people in the world. The poorest areas in the world (Africa, Latin America, Asia) own vast and diverse renewable resources, and they can develop their entire electricity sector based exclusively on renewable technologies, when the industrialized world converts to the efficiency/renewable energy option, and develops the efficiency and renewable technologies of the future.
Environmental friendliness	Except for large-scale hydro and non-sustainable biomass, the environmental impacts of renewable energy are minor. The additional impact is none or very low when the renewable energy technologies are integrated in other human activities, e.g. rooftop solar, wind turbines in industrial areas.
Risk	Except for large-scale hydro and non-sustainable biomass (that could be aggravated by genetic modification techniques), the risks of renewable energy are low and manageable by the human species.
Affordability	The wealthy societies of the world can afford the development and full implementation of renewable energy sources. True that people and societies addicted to faulty low-priced fossil fuels and nuclear power (rolling of the high externality costs) are reluctant to start the transition and conversion to a sustainable energy system. The transition is significant because the four basic change processes of a sustainable development are involved. But this transition is affordable, much more affordable than business-as-usual. Nevertheless, the affordability of an almost full transition to renewable power sources is subject of concern.

A new technology, which allows easier installation on curved surfaces, called thin-film flexible cell is under development. Recently, a US laboratory announced the first development of cells with an efficiency reaching 40.3% [18].

The cost of PV systems is around $5000/kW, which is three to five times more expensive than other power generation methods. This high cost is mainly the result of the restrictions by the extent and quality of the electricity distribution grid, and by the availability of materials. For example, a recent unexpected shortage of PV-grade silicon has increased its price. Despite its current situation, it is forecasted that electricity could be produced at a competitive price by the year 2020 [18]. Its cost is expected to drop to a competitive level once new manufacturing plants come on line with technological advances and improvements.

While the use of biomass has very important benefits such as contribution to the security of fuel supply (see Table 3), lower greenhouse gas emissions, and their support for agriculture, there are also some key concerns and challenges. These include the fact that bioenergy production and policies have mostly not been based on a broad cost-and-benefit analysis at multiple scales and for the entire production chain, which is a particular element for bioenergy's impact on agriculture. For example, while many publications extol the advantages of converting corn or other crops to ethanol, many of these analyses have their limitations as they do not consider the entire system and cycle [18].

For bioenergy production, both crop-based and purpose-grown cellulosic energy plantations, water availability is regarded as one of the possible future constraint. Around 40% of food production today is provided by irrigation, which already consumes massive amount of ground water with around 200 km^3 globally. As a result, boreholes are being sunk chasing falling water tables, as far as 1 km for example, in both India and China. For borehole depths of greater than about 167 m, pumping energy alone would require entire biomass energy that could be grown from the extracted water and the energy return is even negative for greater depths [19].

The conflict between food and bioenergy is already noticeable. During the oil price hike in the summer of 2009, corn prices have risen, as grain was increasingly diverted to ethanol production. In the future, an expanding global population, and thus an increase in agricultural and forestry production as well as bioenergy fuels, can increase the conflict between food and bioenergy further. Global warming can also negatively affect grain yields because of reductions in photosynthetic activity at high temperatures.

Hydroelectricity is mostly used for large scale power productions. However, it depends upon large differences in elevation that may not be available in every parts of the world. One solution to this obstacle is pumped storage, in which water is pumped uphill during times of low electrical demand (off-peak electricity) and goes through the turbines at times of high electrical demand. This system is commonly used in some parts of the world to meet daily requirements for peak electricity [9].

Main disadvantage of hydropower systems is that they are causing various environmental and social problems as the dams are creating an upstream lake of, for example, 600 km [18], and relocating millions of people. Also, significant release of CO_2 and methane caused by hydropower systems in warm climate vegetated regions is another critical drawback.

Climate change has a significant negative effect on the non-intermittent renewable energy sources; hydro and biomass. Hydropower production depends on average annual rainfall, and its annual variation and extremity. As climate change cause extreme or insignificant rainfalls, it can cause severe reductions in hydropower production. Decrease in rainfall results in decrease in hydropotential and, on the other hand, intense rainfall events cause disproportionate soil erosion. It follows that reservoir siltation will increase even more in the future, if negative effects of climate change continue to grow. Increasing siltation rates lower the output from existing hydropower systems as well as the economic viability of building new systems. Also, global warming lowers the share of snowfall on mountain ranges that bring forward the discharge due to annual snowmelt, which results in more temporally skewed stream flows. Another effect of climate change is increased regional temperatures that will increase reservoir evaporation. Therefore, with 40–80 million people displaced to make way for large hydro schemes over the past half century and their often high environmental costs, major hydroelectric expansion will continue to face serious public acceptance issues. The World Energy Technology Outlook (WETO) report, even in the most favorable case, projects only 19 EJ hydro globally for 2050, compared with 10.7 EJ in 2009 [19].

The other source of non-intermittent renewable energy is geothermal energy. Conventional geothermal energy systems are usually preferred for direct heat generation rather than electricity. The depth of the geothermal heat source and its temperature are two crucial parameters for assessing its efficiency and cost. Economic electricity production requires resource temperatures of at least about 150 °C. The cost of wells rises roughly exponentially with depth, and hence the energy costs of produced electricity. The International Energy Agency (IEA) gives the global potential of geothermal electricity production as only 85 GW (about 2.4 EJ/year) over the next 30 years [19].

Incorporation of renewable energy technologies into the main stream of the power generation sector has been constrained by many obstacles, the important one being their higher unit cost of power production. Table 4 gives levelized energy costs (in US-cents/kWh, based on 2006 currency) for electricity generation by the major renewable and non-renewable technologies. Both coal and gas show a clear absolute cost advantage over the renewable technologies. Note that, back-up generation costs associated

Table 3
Some biomass conversion routes to fuel.
Source: Modified from Lior [18].

	RME	Ethanol from sugar or starch crops	Ethanol from woody biomass	Hydrogen from woody biomass	Methanol from woody biomass	Bio-oil from woody biomass
Method	Extraction and esterification	Fermentation	Hydrolysis, fermentation and electricity production	Gasification	Gasification	Flash pyrolysis
Net efficiency of energy conversion	75% (based on all energy inputs)	50% for sugar beet; 44% for sugar cane	60–70% (longer term, with power generation)	55–65%, >60–70% (longer term)	50–60%, >60–70% (longer term)	70% (raw bio-oil)
Short term cost range, ($/GJ)	15–25	15–25 for sugar beet; 8–10	10–15	8–10	11–13	N/A
Long term cost range, ($/GJ)	N/A	N/A	6–7	6–8	7–10	Unclear

Table 4
Cost of traditional and renewable energy technologies, current and expected trends.
Source: Adapted from Owen [24].

Energy source	Technology	Cost of delivered energy (US-cents/kWh)	Expected future costs beyond 2020 as technology matures (US-cents/kWh)
Coal	Grid supply (generation only)	4–6	Capital costs to decline slightly with technical progress. This may be offset by increases in the (real) price of fossil fuels
Gas	Combined cycle (generation only)	3–5	
	Off-peak	3–4	
Delivered grid electricity from fossil fuels	Peak	19–32	
	Average	10–13	
	Rural electrification	32–103	
Nuclear		5–8	4–6
Solar	Thermal electricity (annual 2500 kWh/m^2)	15–23	5–13
	Photovoltaics (annual 1000 kWh/m^2)	64–103	~10
	Photovoltaics (annual 1500 kWh/m^2)	38–64	~6
	Photovoltaics (annual 2500 kWh/m^2)	26–51	~5
Geothermal	Electricity	3–13	1–10
	Heat	0.6–6	0.6–6
Wind	Onshore	4–6	3–4
	Offshore	8–13	3–6
Hydro	Large scale	3–10	3–10
	Small scale	5–13	4–13
Biomass	Electricity	6–19	5–13
	Heat	1–6	1–6
Marine	Tidal barrage	15	15
	Tidal stream	10–19	10–19
	Wave	10–26	6–9

with the intermittency of renewables to ensure reliability of supply are not included in the table. Thus, on purely financial grounds, renewable technologies currently appear to be non-competitive. The cost gap between renewable and conventional power generation sources has however been narrowed significantly over the past two decades and it is expected to continue narrowing as reflected in projected cost levels for 2020 (Table 4). However, the gap is unlikely to be closed quickly enough without significant policy actions to help improved levels of investment in research and development to assist governments to meet their Kyoto Protocol (or other) commitments on global climate change initiatives in any major way [24]. Such an action has been taking place in Ontario, Canada, which started in November 2006 to force utilities to purchase renewable power by setting a fixed price above market rates. This program offers a fixed rate of 11 cents/kWh for small scale hydroelectric, biomass, and wind projects and 42 cents/kWh for solar PV facilities, which are set in 20-year contracts with assured access to the grid. The program signed more than 655 MW of wind, 316 MW of solar PV, 66 MW of hydroelectric, and 67 MW of biomass capacity in just 15 months. The Canadian program was very successful as in less than two years it exceeded its 10 years anticipated target of 1000 MW. More than 1300 MW of contracts were fulfilled by the end of June 2008 [27].

In contrast to fossil fuels, the efficiency of renewable technologies is usually site specific. For example, it would be expected that photovoltaics in higher latitudes would require a higher cost per unit energy than countries located at lower latitudes. In contrast, fossil fuels are internationally traded and thus have a similar cost throughout the world. Therefore, cost comparisons between energy sources should be made on the basis of "optimal conditions" that include the charge of every aspect. For example, photovoltaics are generally "delivered" as distributed electricity and so, its cost should be compared with "delivered" electricity from other sources that include the transmission and distribution costs. In Table 4, cost ranges for delivered electricity are also given. In developing countries, the cost difference is still in favor of fossil fuel technologies outside rural electrification, but the difference is much smaller when delivery cost is not included [24].

Table 5
CO_2 emissions from different electricity generation technologies.
Source: Modified from Owen [24].

Technology	Fuel (tons/GWh)	Extraction (tons/GWh)	Construction (tons/GWh)	Total (tons/GWh)
Coal-fired (Con)	1	1	962	964
Oil-fired	–	-	726	726
Gas-fired	–	-	484	484
Nuclear	~2	1	5	8
Solar thermal	N/A	3	N/A	3
Photovoltaics	N/A	5	N/A	5
Wind	N/A	7	N/A	7
Small hydro	N/A	10	N/A	10
Large hydro	N/A	4	N/A	4
Geothermal	< 1	1	56	57
Wood	−1509	3	1346	−160

Table 5 gives life-cycle CO_2 emissions (in tons/GWh) of the main electric power generation forms. From this table, it is clear that CO_2 emissions from coal and oil-based power generation systems are well beyond those of the "renewable" and are twice those of gas.

In Table 4, the costs of damage to the environment or to people with all other associated effects, which are caused by climate change and GHG emissions, are not included. This category includes damage from acid rain and health damage from oxides of sulfur and nitrogen from fossil fuel power plants and many others. Also, another category that needs to be taken into account is costs associated with climate change such as damage from flooding, changes in agriculture patterns and other effects. Other costs in this category include factors such as power industry accidents (e.g. nuclear plants), visual pollution and noise. The

European Commission's (EC's) ExternE study has estimated human health damages and other non-climate change pollution damages that range from 0.3 to 5.0 US cents/kWh for the coal fuel cycle [24]. Estimates have shown that if damage costs resulting from combustion of fossil fuels are internalized into the price of electricity production, a number of renewable technologies can be financially competitive with coal. However, combined cycle natural gas technology would still have a significant financial advantage over both coal and renewables under current technology options and market conditions. Over the next few decades, the costs of renewable technologies are likely to drop noticeably as technical progress and economies of scale combine to reduce unit-generating costs [24].

To sum up, renewable power generation technologies are increasingly demanded in the marketplace. Unfortunately, relatively high cost, low efficiency and intermittency challenges prevent the possibility of a completely renewable power system in the near future. As a result, nuclear energy is receiving attention because of low greenhouse gas and pollutant emissions. In the following section, nuclear energy will be reviewed.

3. Nuclear energy

Public perception of nuclear energy is improving due to the increasing concerns regarding global warming generated from the use of fossil fuels. But it is still not very good and people have the feeling that they have to choose between greenhouse effect and acid rains associated with fossil fuels use, and severe consequences of possible nuclear accidents, of nuclear wastes, and of use for warfare and terrorism. The nuclear power has an 18% increase in R&D, mainly due to rising public reorganization of the impact of global warming and energy independence concerns [18]. Without permanent and economical solutions to the nuclear waste, massive use of nuclear fission power seems to be obstructed.

Operational technologies of nuclear power are based on the fission of heavy atoms, in which only heat is generated. There are various commercial technologies such as pressurized, boiling and water cooled graphite moderated light water reactors; heavy water reactors; gas-cooled reactors, etc. Also, some new technologies are under development for the future such as breeders and fusion of light atoms [18].

Existing nuclear plants operates at very large scales such as 500, 1000, 1300, and 1500 MW, and larger capacities are planned for the future reactors [29]. Due to technical and economic reasons, they operate at constant full load. They are located at far distances from urban areas and preferably also from industrial mega-complexes due to safety regulations. The steam conditions of the actual cycles make them incompatible for cogeneration as the loss in power output is extreme when steam at about 2 bar pressure is extracted.

Nuclear power generates 16% of global electricity demand. The amount of nuclear power is increasing significantly while, in contrast, the number of reactors is increasing very slightly. This is because new reactors are larger in size/capacity. The new government initiatives started to solve some related problems. These problems include the storage of nuclear wastes that cause strong public opposition. It is particularly because of the very long time, of the order of tens of thousands of years, needed for nuclear waste's surveillance and monitoring. Even though most countries have their own technology to dispose high-level radioactive waste into deep geological repository, it is still difficult to find out suitable sites and to get the public acceptance. This difficulty is mainly due to the fact that high-level radioactive waste contains long-lived hazardous nuclides such as minor actinides (MA: Np, Am, Cm) and long-lived fission products (LLFP: Tc-99, I-129) whose radio-toxicity last for millions of years [31]. Partitioning and transmutation of the long-life radioactive elements seems to be a reasonable method of dealing with this problem. This method is currently applied either in accelerator-driven systems or in futuristic critical reactors.

Despite the unresolved problems of waste storage, proliferation risk, and to some extent safety, nuclear power plants continue to be constructed, especially in countries that have much better access to uranium than to fossil fuels. The amount of uranium in the world seems to be insufficient for substantial long-term operation of nuclear power generation. This situation can only change if breeder reactor technologies improve to a safe and mature level, which is not likely to be achieved in the next couple of decades.

Breeder (Generation IV) reactors are planned to have the following main features with a target date of 2030. Its electricity price is expected to be competitive with that generated by natural gas power plants of 3 ¢/kWh with capital cost of $1000/kW [18]. Its construction time is predicted as 3–4 years with demonstrating safety to regulatory agencies and to the public. The safety attributes would include the following main developments [18]:

- reactor cores that do not melt in an accident,
- coolants that do not react (corrosion and other chemical reactions) with their conduits,
- passive cooling that is typically driven by the natural buoyancy of the coolant rather than by pumps and fans,
- no accident scenarios that require offsite emergency response, and
- high tolerance to human error.

The performance of nuclear power in the sustainable backstop supply criteria is discussed in Table 6. Presently, the basic public interpretation is "there is no solution without nuclear power but it is a part of the solution" [29]. Nuclear power is considered, as a result, an acceptable option as a transition to a complete renewable future. As discussed in the previous section, renewable forms of energy are currently not developed enough, or available on a large scale, to be a significant contributor to the world's energy supply. Thus, it is decisive for energy sectors to solicit a marriage between nuclear and renewable for a cleaner future.

Nuclear power is currently used almost completely to generate electricity and thus cannot be used on a large scale in the transport sector without significant R&D. Nuclear-based hydrogen generation from water is a promising solution. Nuclear-based hydrogen production has the potential to reduce CO_2 emission from the global warming perspective and provide a carbon free energy solution for the future generations. Nuclear reactors can be coupled to a hydrogen production plant utilizing either high temperature electrolysis or a thermochemical cycle, to generate hydrogen environmentally friendly and economically. The cost of nuclear-based water splitting for hydrogen production is around $2/kg H_2 [8]. The technological feasibility and experimentation of key components is one of the main decisive factors in plant viability.

3.1. Energy sources for nuclear-based hydrogen production

In this section, some common nuclear reactor types that are good candidates for nuclear-based hydrogen production will be discussed.

3.1.1. High temperature gas-cooled reactor (HTGR)

Hydrogen production using thermochemical cycles has been studied for decades. Well developed high-temperature gas-cooled

Table 6
Evaluation of nuclear power on the criteria of sustainable backstop supply technology.
Source: Modified from Verbruggen [29].

Criteria	Nuclear power performance
Limitation	Nuclear power on earth can be considered as an unlimited resource only when fusion will be technically, economically and safely possible. The second best unlimited nuclear source (breeders) has failed the practical tests. The once-through use of uranium in fission processes will exhaust the easy recoverable uranium concentrations.
Decision	Nuclear technology and the nuclear fuel cycle require secrecy and protection against intruders. Nuclear material can be abused for state or private terrorism. Decision-making on nuclear projects is mostly of the DAD (Decide–Announce–Defend) type. Citizens are considered not to 'understand' such complex technologies and their fortunes. This is opposed to the minimum requirements of procedural fairness where those directly affected by the decisions must have a voice and representation in the process.
Accessibility	The huge capital and technology intensity of the nuclear option makes this option inaccessible for many developing economies. In addition, proliferation of know-how and nuclear capabilities creates a more dangerous world than the containment and reduction of its spreading, and finally the banning of the nuclear technology in all uses but the medical ones.
Environmental friendliness	Nuclear fission is a carbon-free process. Other emissions (inert gases) in the air are not as massive and diverse as emissions from fossil fuel combustion. Release of radioactive isotopes is the most significant source of contamination; massive releases happen in case of accidents.
Risk	Given the probability of accidents, and given the – from a human perspective – eternal lifetime of radioactive waste, nuclear power is not without risks. Some will consider the risks as minor, some as huge. Risk perception and assessment are circumstantial and personal matters that are difficult to define, measure and compare. Therefore one could call upon societal risk processing institutions and procedures, i.e. the insurance sector. However, given that the risks of nuclear accidents and the eternal horizon of nuclear waste fall out of the range accepted by experienced professional underwriters, it is false to argue that the societal risks of nuclear power are minor, and should be accepted by the lay people of present and future generations.
Affordability	"Safe" nuclear power is too costly to build and operate. When societies accept particular kinds and levels of risks and the wheel of fortune is benevolent, large amounts of nuclear power can be generated at affordable monetary spending (see France over the last decades). The presented accounts however neglect the externality costs of major accidents and of the eternal concern for the high-level waste. Our instruments to gage and assess such externality costs fall short. Up to now this is used as a validation that the costs are low, but in fact is an extra argument to adopt a precautionary attitude and policy.

reactor (HTGR) is one of the main thermal energy sources for these nuclear-based hydrogen production processes. Most of the thermochemical cycles operate at temperatures as high as 800 °C, which represent an easily available temperature level for HTGR. The HTGR is one of the most suitable nuclear reactors to couple with high temperature thermochemical cycle of hydrogen production, owing to its capability of producing high-temperature heat close to 1000 °C. In addition, these high temperatures assure an efficient energy conversion.

3.1.2. Advanced gas reactor (AGR)

The AGR is a commercial thermal reactor that consists of uranium oxide fuel pellets core in stainless-steel cladding within graphite blocks. The carbon dioxide acts as a coolant while graphite as a moderator. The achievable temperature of the coolant at the reactor output during normal operation is around 650 °C, which can be driven up to 750 °C with new designs of further technological developments. The carbon dioxide circulates through the core at 4.3 MPa. However, in the future design and implementation, there is a potential to increase the operating pressure in order to couple it with a direct cycle supercritical CO_2 power conversion system. This coupled system can consequently enable high-efficiency and economic hydrogen production through steam electrolysis at medium temperatures.

3.1.3. Advanced high-temperature reactor (AHTR)

A comparatively new molten-salt-cooled reactor concept, called advanced high-temperature reactor (AHTR), is developed to provide very high-temperatures of 750–1000 °C [11]. The AHTR utilizes the solid coated-particle fuel in a graphite-matrix similar to the MHR, but a molten-fluoride-salt as coolant. This technology basically combines the high-temperature fuel from the HTGR with a denser coolant for the molten salt reactor. The proposed design operates at atmospheric pressure with coolant exit temperature of 1000 °C. This high grade heat generation from the HTGR enables efficient, low-cost hydrogen and electricity production. The reactor is proposed to be built in large capacities such as 2000 MW with passive safety systems for decay heat removal.

3.1.4. Modular helium reactor (MHR)

The MHR consists of prismatic blocks of graphite core that allow coolant flow and contains ceramic fuel. The processing pressure of the MHR is about 7 MPa. The core design can provide passive safety by operating at high temperatures during transients and by large thermal inertia. The temperature of the coolant at the reactor output is presently designed to achieve temperatures around 850 °C, but proposed to achieve 1000 °C in the future designs. Consequently, it can provide high grade/capacity heat at a convenient level to produce both hydrogen and electricity.

4. Hydrogen

Hydrogen is expected to play a significant role as an energy carrier in the future. Hydrogen can be used as fuel in almost every application where fossil fuels are utilized today. In contrast to fossil fuel, its combustion is without harmful emissions, disregarding only NO_x emissions that can be effectively controlled. In addition, hydrogen can be transformed into useful forms of energy more efficiently than fossil fuels. Hydrogen is as safe as other common fuels, despite its common perception. Yet, hydrogen is not an energy source and hence it does not exist in nature in its elemental form. Therefore, hydrogen must be produced from water, the most abundant source of hydrogen, or from other sources. However, splitting of water for hydrogen production necessitates energy that is higher than the energy that can be obtained from the produced hydrogen. Therefore, hydrogen is considered an energy carrier—a suitable form of energy like electricity [2].

It is commonly accepted that hydrogen is one of the promising energy carrier and that the demand for it will increase greatly in the near future, for it can be utilized as a clean fuel in diverse energy end-use sectors including the conversion to electricity with no CO_2 emission. It can also be stored and transported over

long distance with lower loss compared to electricity. Hydrogen produced from nuclear energy can contribute to ongoing efforts to address global warming issues, as well. Hydrogen is usually produced from carbonized hydrogen and oxidized hydrogen; that is, from fossil fuel and water, by providing large amount of energy such as heat and electricity. So, a large amount of hydrogen can be generated economically with nuclear energy and hence, CO_2 emissions be reduced simultaneously. In this regard, commercialization of hydrogen generation systems using nuclear and renewable energy sources, instead of fossil fuels, is desired [31].

Hydrogen used as an energy carrier enables power transportation to end-use, without any pollutants and greenhouse gas emissions. Moreover, hydrogen can be produced efficiently with very low emissions from various renewable and more sustainable primary energy sources such as wind, solar, and nuclear power, from biogases and industrial waste streams, as well as from domestic fossil fuels such as natural gas and coal. However, before hydrogen can be considered for widespread use as an energy carrier, considerable technological improvements in hydrogen production, transfer and storage are needed. Furthermore, once hydrogen production and storage capabilities are notably improved, large investments in hydrogen distribution and fueling infrastructure will be needed before widespread use is possible. Nevertheless, remarkable progress in improving the efficiency and lowering the cost of hydrogen production has been made [3].

Hydrogen systems can provide feasible, sustainable alternatives to meet the world's energy requirements. Hydrogen is suitable for all energy sectors such as transportation, buildings, utilities and industry. It can supply storage options for base-load (geothermal), seasonal (hydroelectric) and intermittent (PV and wind) renewable resources. Also, it can decrease the climate impacts of continued fossil fuel utilization, when combined with emerging decarbonization technologies. However, hydrogen energy systems still face many technical and economical barriers that must first be surmounted, for it to become a competitive energy carrier. Improvements must be made in hydrogen production, storage, transport and utilization technologies along with the integration of these components into complete energy systems. Nations have come together under the auspices of the International Energy Agency's (IEA) hydrogen program to cooperate with each other, and address the important barriers that hamper hydrogen's worldwide acceptance to accelerate the advancement of hydrogen technologies and realize a hydrogen future. Through well-structured, collaborative projects, experts from around the world deal with many of the technical challenges that the hydrogen community is faced with. These collaborations have already led to remarkable advances in renewable hydrogen production and storage materials, and to the developments to evaluate and optimize integrated hydrogen energy systems. The IEA launched the Production and Utilization of Hydrogen Program, known as the Hydrogen Agreement, in 1977. This program aims to advance hydrogen production, storage and end-use technologies and to accelerate hydrogen's acceptance and widespread use [7].

Although hydrogen is usually accepted to be a clean fuel, it is essential to know that the method of production plays a very significant role in the level of environmental impact. Presently, fossil fuels and water are two main sources of hydrogen. Fossil fuels provide 96% of the hydrogen produced today, and steam reforming of natural gas accounts for a massive 48% [8].

There are many contradictory views on the hydrogen economy. The proponents claim that future generations will depend on hydrogen, produced from fossil fuels in the short term and nuclear and renewable sources in the long run. Accepting the depletion of fossil fuels and considering environmental concerns, majority agrees that a new energy solution is needed so as to provide a dependable and sufficient energy network for future generations. It is uncertain whether the electricity network can handle the dramatic increase in load that might result from turning to a solely electricity economy to replace fossil fuels. Therefore, it is likely that hydrogen and electricity will both be used in the future to meet public demand and needs.

Nuclear energy and fossil fuels, with carbon dioxide sequestration, are currently two main technologies that can provide high volume, large scale, and centralized hydrogen production. The electricity and heat from nuclear plants can be coupled with electrolysis or thermochemical cycles to produce hydrogen. Hydrogen from the steam reforming of fossil fuels is a verified technology, yet the CO_2 emissions must be sequestered if there is to be an environmental gain. This is not ideal in the long term and the technology still needs further development.

Most of the technological requirements of hydrogen production, storage, and utilization have already been developed to a level where they can rival the existing energy technologies. Table 7 shows the technologies for hydrogen production, storage, distribution, and utilization.

The hydrogen economy is an unavoidable energy system of the future and the transition to a hydrogen economy may have already begun. To fulfill all the energy needs of human civilization, available energy sources (preferably the renewables) will be used to generate hydrogen and electricity as energy carriers. In the future there will always be a need for convenient, clean, safe, efficient and versatile energy carriers or forms of energy that can be delivered to the end user regardless of the energy sources. One of these energy carriers is electricity that is already being used universally. Hydrogen is another clean, efficient and multipurpose energy carrier, which may supplement electricity very well.

Table 7
Significant hydrogen technologies.

Hydrogen				
Resources	***Production***	***Storage***	***Distribution***	***Utilization***
Fossil fuels	Electrolysis	Underground gas storage	Pipelines	Combustion in internal combustion engines and turbines
Nuclear	Thermochemical processes	Above ground gas storage	Gaseous and liquid containers by road and/or rail transportation	Direct steam generation by hydrogen/oxygen combustion
Renewables	Hybrid processes	Vehicular pressurized tanks		Catalytic combustion of hydrogen
		Liquid hydrogen storage		Electrochemical electricity generation (Fuel cells)
		Metal hydride storage		
		Other novel storage methods		

Together these two carriers, electricity and hydrogen, may address all the needs and form an energy system that is permanent and independent of energy sources. Hydrogen has some unique characteristics that make it an ideal energy carrier, namely [25]:

- It can be produced from and converted into electricity at a relatively high efficiency.
- Raw material for hydrogen production is water, which is abundant.
- Hydrogen is a completely renewable fuel, since the product of hydrogen utilization (either through combustion or through electrochemical conversion) is pure water or water vapor.
- It can be stored as liquid, gas, or solid (metal hydrides).
- It can be transported over large distances using pipelines, tankers, or rail trucks.
- It can be converted into other forms of energy in more ways and more efficiently than any other fuel, i.e., in addition to flame combustion (like any other fuel) hydrogen may be converted through catalytic combustion, electro-chemical conversion, and hydriding.
- Hydrogen as an energy carrier is environmentally compatible. It produces small amounts of NO_x, if it is burned with air at high temperatures.

Fig. 1 demonstrates a global energy system in which electricity and hydrogen are produced from existing energy sources and consumed in many applications. In particular, both hydrogen and electricity match renewable energy sources well, by presenting them to the end user in a suitable form and at a suitable time. Depending on the location, electricity may be used directly or converted to hydrogen.

4.1. Hydrogen production

It is difficult to compete with the cost of fossil resources as long as they are reasonably accessible. The primary reason for the transition to hydrogen, however, is reduction of CO_2 emission, and thus, comparisons of the hydrogen production processes should include the effect of CO_2 reduction. Because hydrogen is a synthetic fuel and a secondary medium of energy, both raw material and energy are needed for production. Water is abundant as a raw material but hydrogen production decomposition of water requires large amounts of energy. Therefore, carbon dioxide emission, efficiency and costs for both material and energy consumption must be considered in comparison of hydrogen production technologies. Table 8 summarizes the comparison, where features are rated from $--$ to $++$. Note that biomass is regarded as "carbon-free" because its origin is the atmosphere, even though it generates CO_2 when producing hydrogen. For raw materials, natural gas is preferred over coal or oil, as seen in Table 8.

Despite the results in Table 8, currently, hydrogen production is mainly from the fossil resources for both raw material and energy. The typical process is steam reforming that is achieved with an endothermic reaction in the form of $C_nH_m+nH_2O=nCO+(m/2+n)\ H_2$. This reaction requires a large amount of heat that is usually supplied by the oxidation of a part of the hydrocarbon [15]. However, hydrogen should be produced from water, rather than fossil sources as done presently, in order to minimize greenhouse gas emissions and the following undesirable environmental impact.

One of the most efficient methods for meeting increasing energy needs could be using nuclear power to produce electricity and hydrogen, thus providing effective and universal energy carriers. Nuclear power plants produce heat that can be used directly or converted to electricity for the production of hydrogen. The nuclear energy driven thermochemical cycle is one of the potential water-splitting processes for producing hydrogen that can compete with fossil fuel based productions.

Electrolysis of water is another well-known technology, but subject to low overall efficiencies due to inefficiency of the thermal energy to electrical energy conversion in thermal power stations. This inefficiency can be avoided through thermochemical cycles, in a sequence of chemical reactions yielding a net reaction of decomposition of water [28]. Thermochemical water splitting is a chemical process that is not limited by Carnot's efficiency. It is a combination of endothermic and exothermic reactions, and it must discard low temperature heat

Table 8
Comparison of raw materials for hydrogen.
Source: Konishi [15].

	Reaction	CO_2 emission	Resource
Coal	$C+2H_2O\rightarrow CO_2+2H_2$	$--$	$+$
Oil	$CH_2+2H_2O\rightarrow CO_2+3H_2$	$-$	$-$
Gas	$CH_4+2H_2O\rightarrow CO_2+4H_2$	$+-$	$+-$
Water	$2H_2O\rightarrow O_2+2H_2$	$+$	$+$
Biomass	$CH_2O+H_2O\rightarrow CO_2+2H_2$	$+$	$++$

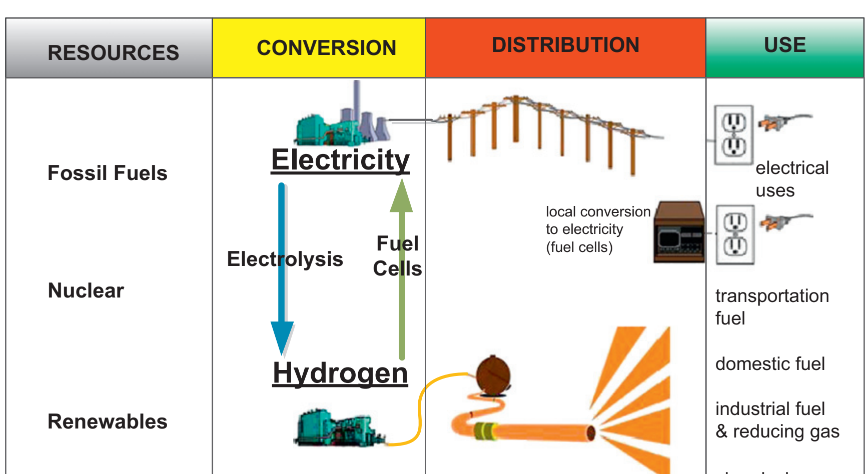

Fig. 1. Hydrogen/electricity energy system (modified from [25]).

resulted from exothermic reaction, while high temperature reaction is endothermic [15].

Centralized hydrogen production is favored by production and transportation economics, in most parts of the world. This is a system with characteristics independent of the choice of hydrogen production technology. Hydrogen production is a chemical process with cost-capacity scaling factors (between 0.6 and 0.7) that strongly favor large plants. Today the largest hydrogen consumers are refineries and ammonia (fertilizer) plants that typically use natural-gas-to-produce hydrogen with a large capacity that would require three 1000-MW nuclear plants using electrolysis to match production [9].

To produce hydrogen, the hydrogen bonds in hydrocarbons or water need to be broken and then hydrogen need to be separated from the reaction mixture. Four classes of H_2 production options are under development [12] as follows:

- electrolysis (electricity + H_2O [liquid] → H_2 + O_2);
- high-temperature electrolysis (electricity + H_2O [steam] → H_2 + O_2);
- hybrid cycles (electricity + heat + H_2O → [cyclic chemical reactions] → H_2 + O_2);
- thermochemical cycles (heat + H_2O → [cyclic chemical reactions] → H_2 + O_2).

The near-term hydrogen production option is electrolysis, while the longer term options involve using heat to convert water to hydrogen and oxygen. Heat is less expensive than electricity because the cost of converting heat to electricity and associated losses is avoided. For example, estimates have made that the cost of nuclear thermochemical H_2 production could be 60% lower than nuclear H_2 production by the electrolysis of water [10]. Thermochemical H_2 production involves the conversion of thermal energy to chemical energy (H_2) while electrolysis involves the conversion of thermal energy to electricity and then conversion of electricity to chemical energy.

The main processes for hydrogen production include steam reforming of natural gas, catalytic decomposition of natural gas, partial oxidation of heavy oil, coal gasification, water electrolysis, thermochemical cycles, and photo-chemical, electrochemical and biological processes. The first four processes are based on fossil fuels. Currently (and probably in the near future), methods for obtaining hydrogen using carbon compounds as the raw material remain as the main methods. However, the raw-materials and ecological limitations of steam conversion of methane are motivating the development of processes to produce hydrogen from water. The most attractive of these alternative methods in the context of nuclear power are electrolysis and thermochemical and thermoelectrochemical cycles. Fig. 2 presents an overview of nuclear-based hydrogen production technologies.

4.1.1. *Steam conversion of methane*

A large amount of hydrogen is produced primarily by steam conversion of the methane in natural gas. Steam and heat at 750–850 °C separates hydrogen from the carbon base in methane on catalytic surfaces in chemical steam reformers. In the first step, methane and water vapor are converted into hydrogen and carbon monoxide by a chemical reaction (the synthesis gas). Next, in the "shift reaction" carbon monoxide and water are converted into carbon dioxide and hydrogen in the range of 200–250 °C. For the endothermic process, about half of the initial gas is consumed. The system consists of two main parts, nuclear and process. Nuclear part generates the synthesis gas, while in process part the input gas is used to produce the final product. Fig. 3 shows the principle of steam methane reforming, and based on this figure its chemical formula is expressed as $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$. The heat of this endothermic reaction is 185 kJ, which results in 46.25 kJ per kmol hydrogen produced [5].

4.1.2. *Thermochemical and thermoelectrochemical cycles*

Currently, about 90% of hydrogen is produced by a steam reforming process, mainly from methane. In this process, combustion

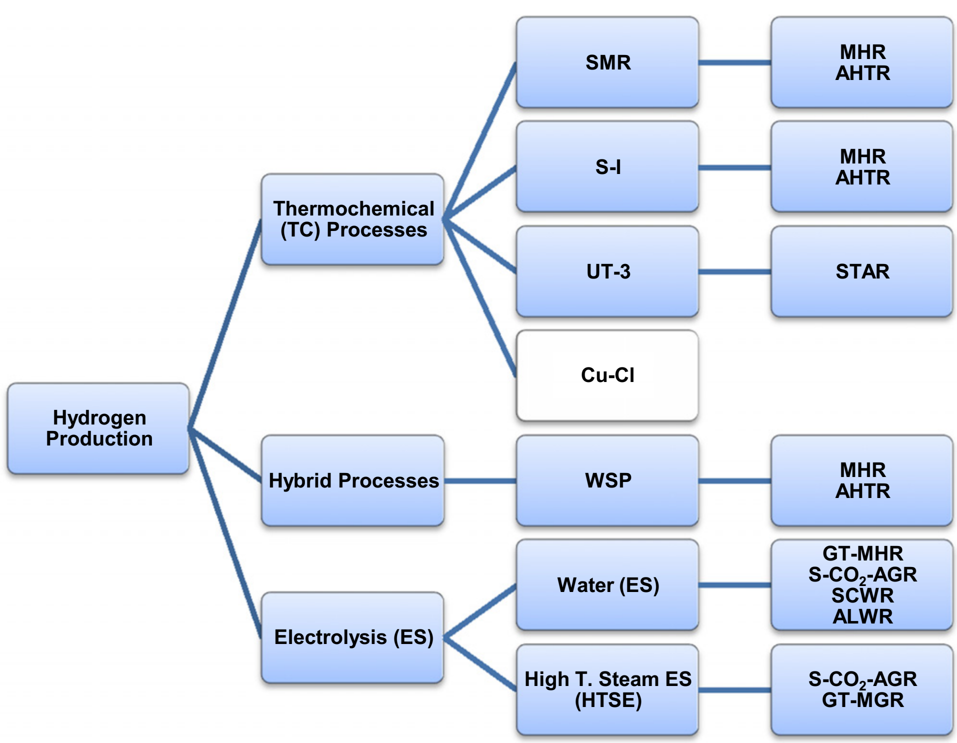

Fig. 2. Technology options for nuclear hydrogen production (modified from [33]).

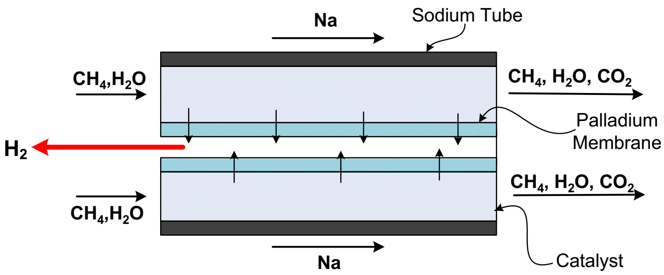

Fig. 3. Principle of membrane reformer (adapted from [5]).

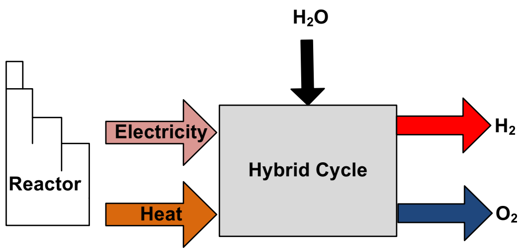

Fig. 4. Simple coupling of an electrothermochemical water-splitting process, a nuclear reactor, and a power conversion system for hydrogen production.

heat of fossil fuel is supplied for the chemical reaction of steam reforming, approximately 0.9 kg-CO_2 to generate 1 Nm^3 H_2. The electrolysis of the water also exhausts more than 1.6 kg CO_2 for 1 Nm^3-H_2 as electricity is generated from fossil fuels [31]. A clean process of hydrogen generation without CO_2 emission is possible by means of the electrolysis of the water using electricity supplied from a Light Water-cooled Reactor (LWR). The efficiency of this process, on the other hand, is low because of the inefficient electricity generation of nearly 35%. Therefore, there is still need for a clean hydrogen production technology with high efficiencies. Thermochemical cycles are good candidates, in which water splits into hydrogen and oxygen using a series of chemical reactions. All chemical intermediates are recycled internally within the process so that water is the only raw material and hydrogen and oxygen are the only products.

High temperatures, such as 2500 °C and above, are required for direct thermal decomposition of water into hydrogen and oxygen [32]. However, a sequence of chemical reactions can be used to decompose water thermally at lower temperatures. This sequence of chemical reactions, namely thermochemical cycles, perform several functions in continues cyclic base such as binding water, splitting hydrogen and oxygen from the water, and recovering the reagents. It is possible, in principle, to decompose water with heat at lower temperatures by combining high-temperature endothermic chemical reactions and low-temperature exothermic chemical reactions that result in the decomposition of water. The process works like a chemical engine to produce hydrogen by absorbing high-temperature heat in the endothermic decomposition and discharging low temperature heat in the exothermic reactions. Figs. 4 and 5, respectively, show schematics for thermochemical processes that do not require electricity input and electrothermochemical processes that require electricity input in addition to thermal energy input.

The concept of thermochemical production of hydrogen from water was first proposed in the 1960s. At standard temperature and pressure, the free energy and enthalpy changes of the direct water decomposition are $\Delta G = 56.7$ kcal/gmol and $\Delta H = 68.3$ kCal/ gmol, respectively. The ΔG for the reaction becomes negative above 4400 °C that causes considerable problems with materials and separations rendering the direct decomposition infeasible. The work required for the one step process can be

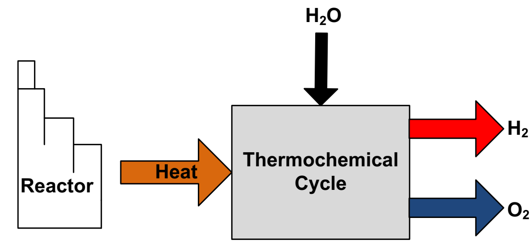

Fig. 5. Simple coupling of a thermochemical water-splitting process and a nuclear reactor for hydrogen production.

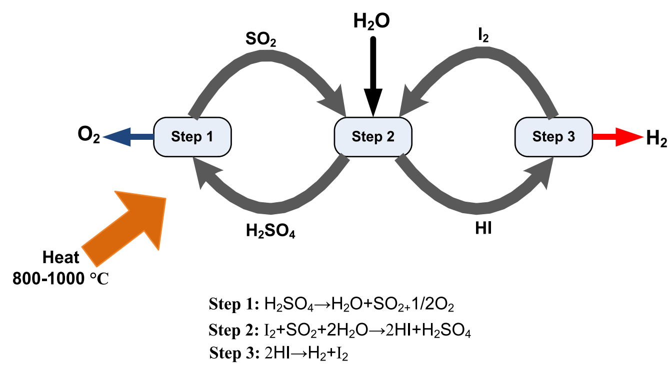

Fig. 6. Iodine–sulfur process for thermochemical production of H_2 (adapted from [30]).

reduced by increasing the operating temperature above 1100 °C. In a multi-step process, it is, in theory, possible to decrease the work requirement to as low as zero by operating reactions with positive entropy changes at high temperatures and reactions with negative entropy changes at low temperatures. No two-step cycle is possible below 1100 °C limit. Consequently, all possible cycles will have three or more steps.

A thermochemical process for producing hydrogen with an efficiency of up to 50% employs a sequence of chemical reactions that require heat at temperatures below 1000 °C. A high-temperature reactor can serve as the heat source for thermochemical decomposition of water. Electrolysis and plasma can be used, together with heat, to produce hydrogen at individual stages of such processes. Many combinations of chemical reactions have been studied. Some examples are as follows:

4.1.2.1. Iodine–Sulfur Cycle. The Iodine Sulfur (IS) process consists of the following three chemical reactions:

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (1)$$

$$2HI \rightarrow I_2 + H_2 \quad (2)$$

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2O_2 \quad (3)$$

The principles for the IS process are illustrated in Fig. 6. The reaction in Eq. (1) is called Bunsen reaction, in which exothermic sulfur dioxide (SO_2) gas absorption takes place in the liquid phase at 20–100 °C. Gaseous SO_2 reacts with iodine (I_2) and water (H_2O) to generate an aqueous solution of hydriodic acid (HI) and sulfuric acid (H_2SO_4). Then the two kinds of acids that are produced at the end of reaction are separated by liquid–liquid phase separation in the existence of excess iodine. The HI breakdown reaction in Eq. (2) generates hydrogen with a low endothermic heat of reaction at 300–500 °C in the gas phase. The reaction can also be carried out in the liquid phase. The H_2SO_4 decomposition reaction in Eq. (3) is an endothermic that produces oxygen (O_2) at the end. This reaction proceeds in two stages; first, gaseous H_2SO_4

decomposes into H_2O and SO_3 at 400–500 °C. Second, SO_3 decomposes into SO_2 and O_2 at about 800 °C with the help of a solid catalyst. By carrying out these three reactions in sequence, water is decomposed into hydrogen and oxygen as a net result of cycle [30].

4.1.2.2. ISPRA Mark 9 Cycle. The ISPRA Mark 9 thermochemical cycle is illustrated in Fig. 7. The cycle consists of three steps cycle, involving iron chlorides as shown below:

1.
$$\text{Decomposition of Fe(III) chloride}: 6FeCl_3 \rightarrow 3Cl_2 + 6FeCl_2 \quad (4)$$

2.
$$\text{Hydrolysis}: \ 6FeCl_2 + 8H_2O \rightarrow 2Fe_3O_4 + 12HCl + 2H_2 \quad (5)$$

3.
$$\text{Chlorination}: \ 3Cl_2 + 2Fe_3O_4 + 12HCl \rightarrow 6FeCl_3 + 6H_2O + O_2 \quad (6)$$

$$\text{Netreaction}: \ 2H_2O \rightarrow 2H_2 + O_2 \quad (7)$$

The hydrolysis reaction is conducted at the highest temperature in the cycle, such as 650 °C. The decomposition of Fe(III) chloride is conducted at 430 °C, and the chlorination at 150 °C [28].

4.1.2.3. Hybrid sulfur cycle. The hybrid sulfur cycle, which is shown in Fig. 8, was developed by Westinghouse. In the cycle, H_2SO_4 is decomposed to SO_2 at high temperatures around 850 °C to produce O_2. Then, SO_2 is converted back to H_2SO_4 in a PEM electrolyzer at 80 °C to produce H_2. Overall, only water and energy are consumed to produce H_2 and O_2 as a net result [26].

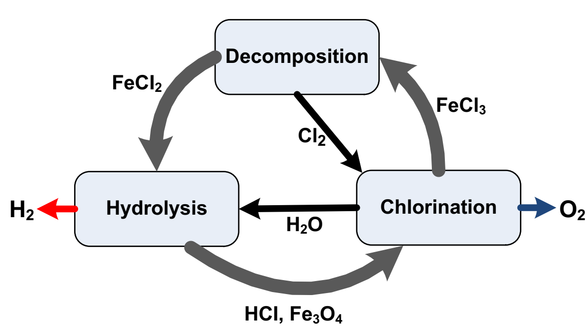

Fig. 7. Flow diagram for the ISPRA Mark 9 hydrogen production process (adapted from [28]).

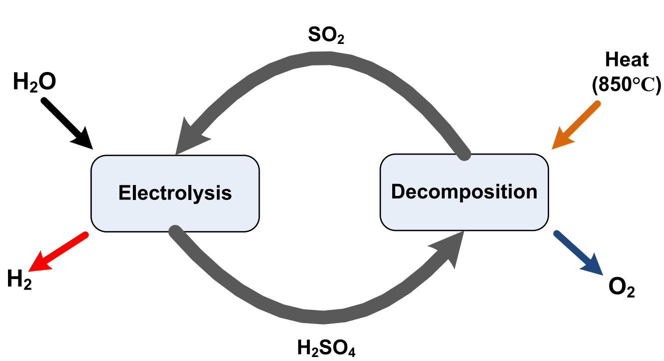

Fig. 8. A schematic of the hybrid sulfur cycle (adapted from [26]).

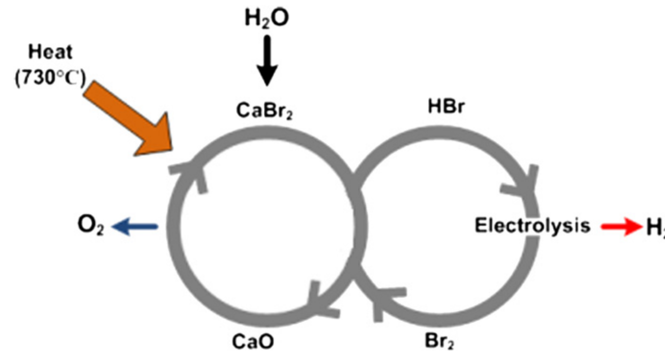

Fig. 9. A schematic of the Ca–Br cycle (adapted from [26]).

4.1.2.4. Ca–Br cycle. In the calcium–bromine cycle, as illustrated in Fig. 9, CaO and $CaBr_2$ are recycled in fixed bed reactors at high temperatures (e.g. 730 °C) and O_2 produced. On the other hand, HBr is converted to Br_2 in a PEM electrolyzer at 80 °C to produce H_2. Overall only water and energy are consumed, and H_2 and O_2 are produced.

4.1.2.5. Cu–Cl cycle. More than three hundred thermochemical cycles have been reported in the literature. However, many of these thermochemical cycles have drawback of very high process temperature requirements. Most thermochemical cycles (e.g. HTE, and the HyS and SI cycles) require process heat at high temperatures, exceeding 850–900 °C that can cause very challenging engineering and material problems. On the other hand, existing nuclear power plants in North America are typically water-cooled plants operating at 250–500 °C, which cannot satisfy above mentioned high temperature thermochemical cycles to produce nuclear-based hydrogen. Therefore, there is a considerable need for a low temperature thermochemical hydrogen production cycle to couple with existing low temperature nuclear reactors.

Recently, Atomic Energy of Canada Limited and Argonne National Laboratory in the U.S. have been developing a low-temperature thermochemical cycle named copper–chlorine (Cu–Cl) [16,17]. This cycle is designed to accommodate heat sources around 500–550 °C. Such a cycle can be more readily incorporated with nuclear reactors and mitigate the demands on construction materials. Many types of nuclear reactors such as the supercritical water reactor, CANDU Mark 2, the lead cooled reactor and the high temperature gas reactor can be used as a heat source. For this temperature range, the Cu–Cl cycle is one of the most promising (see Fig. 10). Several Cu–Cl cycles have been examined in the laboratory and various alternative configurations are identified. Proof-of-principle experiments that demonstrate the feasibility of the processes have been carried out and a preliminary assessment of the cycle efficiency has demonstrated its potential [20–23].

4.2. Hydrogen storage

Hydrogen storage is an important parameter for technical and economical viability of hydrogen fuel systems; without it, a hydrogen economy is difficult to attain. Currently, there is agreement in the automotive industry that the on-board storage of hydrogen is one of the critical bottleneck technologies for the future. Still, no approach exists that can comply with the technical requirements for a range greater than 500 km [1], and fulfilling all the performance parameters. The physical limits for the storage density of compressed and liquid hydrogen have nearly been reached, but there is still potential for developing solid materials for hydrogen storage, such as metal hydrides.

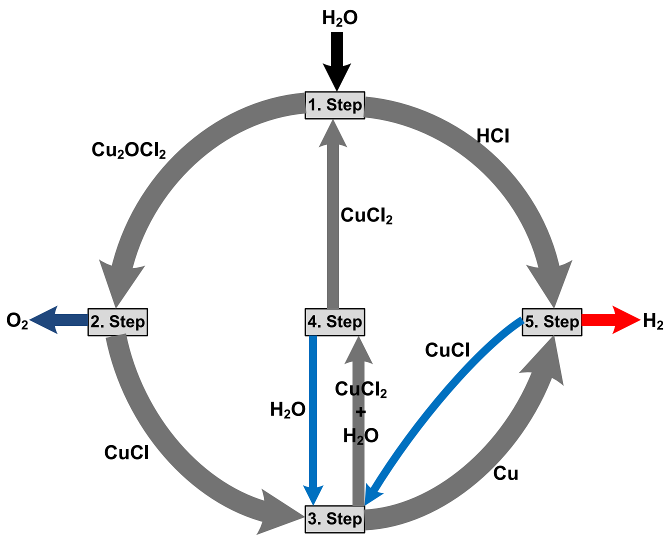

Fig. 10. Five step Cu–Cl thermochemical cycle for hydrogen production.

One of the crucial technological barriers to the extensive use of hydrogen is the lack of a safe, low-weight and low-cost storage method. Hydrogen contains more energy on a weight-for-weight basis than any other substance. In contrast, it has a very low energy density per unit volume since it is the lightest chemical element in the periodic table. High-pressure gas containers and cryogenically cooled (liquefied) liquid hydrogen are two commonly used storage options. One drawback of these methods is a high energy requirement, for instance up to 20% of the energy content of hydrogen needed to compress the gas and up to 40% to liquefy it [6]. A crucial issue for the use of high-pressure and cryogenic storage centers is public perception and acceptance associated with the use of pressurized gas and liquid hydrogen containment. Therefore, hydrogen storage requires some major scientific and technological developments to solve these critical problems. For instance, several classes of solid-state hydrogen storage materials, which show higher energy density than that of liquid hydrogen, are under development. Yet, further research and improvement is required to improve their hydrogen absorption/desorption characteristics.

Necessity for an efficient storage method is the central challenge for variable electricity production. Hydrogen, on the other hand, can be stored economically for days, weeks, or months in large underground facilities with the same technology used to store natural gas. Significant progress has been made in hydrogen storage capabilities. For example, compressed storage has been very successfully demonstrated at 350 and 700 bars [3]. Also, liquid and metal hydride storage technologies have been significantly improved in the recent years. Furthermore, some novel methods such as glass microspheres, poly-hydride complexes and alanates have been significantly advanced.

Hydrogen storage on a small scale is up to two times more expensive than on a large scale. The characteristics of centralized storage imply economic penalties for decentralized hydrogen production systems. For example, collector pipelines need to be used to move hydrogen to centralized storage. A few example of large scale centralized hydrogen storage facilities exist in Europe and the United States.

Hydrogen can be stored underground in old mines, caverns, aquifers, and depleted petroleum and natural gas fields for large-scale storage. Also, large scale fuel cells in MW or kW power plant size can be coupled with this stored hydrogen for distributed power generation. This large scale underground hydrogen storage and fuel cell coupled system can overcome daily and seasonal divergence between energy source availability and demand. Therefore, large scale underground hydrogen storage is likely to be technologically and economically feasible.

Hydrogen storage systems of the same type and the same energy content will be more expensive by approximately a factor of three compared to natural gas storage systems, because of hydrogen's lower volumetric heating value [25]. Hydrogen liquefaction is an energy exhaustive process that requires amounts of energy equal to about one fourth of the energy in liquefied hydrogen. Hydrogen liquefaction and use of liquid hydrogen is usually practiced only when attaining high storage density is very necessary, such as in aerospace applications. Also, some prototype hydrogen-powered automobiles as well as commercially-available automobiles also use specially developed liquid hydrogen tanks. Table 9 provides a list of hydrogen storage types and densities.

4.3. Hydrogen distribution

Various hydrogen transport and distribution options are available; including delivery of compressed gaseous and liquid hydrogen by trucks, and of gaseous hydrogen by pipelines. Pipelines have been used for hydrogen distribution for more than 50 years, with 16,000 km of hydrogen pipelines around the world [1]. Majority of these pipelines supply hydrogen to refineries and chemical plants. The technical and economic effectiveness of each transport option depends on transport volumes and delivery distances. For large quantities and long distances generally pipelines are preferred. On the other hand, liquid hydrogen trailers are useful for smaller volumes and long distances, while compressed gaseous hydrogen trailers are suitable for small scales over short distances. Pipelines have high capital costs but very low operating cost of compressor power. In contrast, liquid hydrogen has a high operating cost mainly for the electricity needed for liquefaction but lower capital costs depending on the quantity of hydrogen and the delivery distance. Distance is also an important factor to decide between liquid and gaseous trailers. The cost of hydrogen transportation on average vary between 0.3 and 1.3 \$/kg H_2 [1]. Note that the distribution pipelines must be made of non-porous, high quality materials such as stainless steel because of the specific physical and chemical properties of hydrogen. As a result, the capital cost of a hydrogen pipeline is up to two times higher than those for natural gas pipelines for a given diameter [1].

For a unit energy throughout, hydrogen transmission through pipelines requires larger diameter piping and more compression

Table 9
Hydrogen storage types and densities.
Source: Modified from Sherif et al. [25].

	Storage density	
	kg H_2/kg	kg H_2/m^3
Large volume storage (10^2–10^4 m^3)		
Underground storage		5–10
Pressurized gas storage(above ground)	0.01–0.014	2–16
Metal hydride	0.013–0.015	50–55
Liquid hydrogen	~1	65–69
Stationary small storage (< 100 m^3)		
Pressurized gas cylinder	0.012	~15
Metal hydride	0.012–0.014	50–53
Liquid hydrogen tank	0.15–0.50	~65
Vehicle tanks (0.1–0.5 m^3)		
Pressurized gas cylinder	0.05	15
Metal hydride	0.02	55
Liquid hydrogen tank	0.09–0.13	50–60

power than natural gas. However, the recompression stations could be placed twice as far apart, due to lower pressure losses in the hydrogen. Large-scale transmission cost of hydrogen is about 1.5–1.8 times larger than that of natural gas but lower than that of electricity for distances greater than 1000 km [25].

Hydrogen can be locally transported and distributed as both gas and liquid, by pipelines or in special cases in containers by road and rail transportation to match the consumption to demand. In some countries, gaseous and liquid hydrogen carriage is subject to strict regulations and constraints ensuring public safety. The gaseous or liquid transportation of hydrogen in a discontinuous mode is usually used by occasional or low volume users. This is because, the cost of discontinuous transport can be very high, up to 2–5 times the production cost [25]. Gaseous hydrogen is generally transported in pressurized cylindrical vessels at about 200 bars. These cylindrical vessels are arranged in frames adapted to road transport with unit capacity of about 3000 m^3. Such frames are installed by distribution companies at the user site to serve as a stationary storage.

Hydrogen is commonly known as posing risks if not properly handled and controlled. However, the risk of hydrogen should be considered and fairly judged relative to common fuels such as gasoline, propane or natural gas. The specific physical characteristics of hydrogen are quite different from those of common fuels. Some of those properties make hydrogen potentially less dangerous as others could make it more hazardous in specific situations. For example, hydrogen has a greater tendency to escape through small openings than other liquid or gaseous fuels, since it has the smallest molecule. For instance, the tendency of hydrogen to leak through holes or joints of low pressure fuel lines could be 1.26–2.8 times faster than that of natural gas, due to properties of hydrogen such as density, viscosity and diffusion coefficient in air. However, the natural gas leak would result in more energy release since it has over three times energy density per unit volume [25].

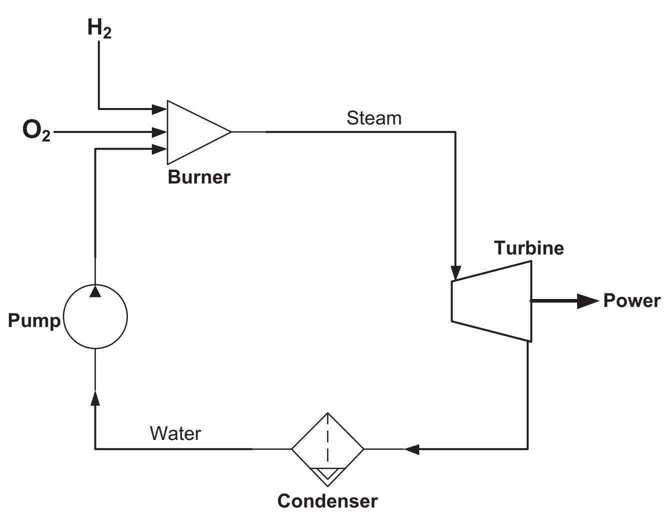

Fig. 11. Oxygen–hydrogen–water steam cycle (adapted from [9]).

4.4. Hydrogen-to-electricity conversion

Fuel cells, steam turbines, or other technologies can be used to produce electricity from hydrogen. The equipment to convert the fuel to electricity should have low capital costs for favorable economics. Fuel cells and steam turbines have been identified for conversion of hydrogen to electricity at higher efficiencies and lower capital costs than commercial fossil fuel methods. The steam turbine option is described in Fig. 11. Hydrogen, oxygen, and water are supplied directly to a burner to produce steam at high pressure and temperature. Water is added to control and lower the peak temperatures since the combustion temperature of a pure hydrogen–oxygen flame is far beyond the limits of construction materials. The process is similar to a low-performance rocket engine. Finally, the produced steam is fed directly to a very high-temperature turbine that drives an electric generator. It is expected that peak steam temperatures at the inlet of the first turbines can approach 1500 °C using advanced gas-turbine technology with actively cooled blades [9].

In fuel cells, an electrochemical reaction that releases heat takes place to produce electricity and water. Usually, only hydrogen and oxygen are consumed in the reaction. Conventional electricity generation takes place in a three-stage conversion process of chemical energy, thermal energy and mechanical energy into electricity. In contrast, fuel cells convert chemical energy directly into electrical energy [1].

Many types of fuel cells which are suitable for various energy applications have been developed. All types of fuel cells, however, share the same basic design of two electrodes anode and cathode, which are separated by a solid or liquid electrolyte or a membrane. Hydrogen or a hydrogen-containing fuel and air are fed into the anode and cathode of the fuel cell, and the electrochemical reactions take place at the electrodes by the help of catalysts. The electrolyte enables transfer of ions between the electrodes, as the excess electrons flow through an external circuit to generate electricity. Fuel cells are classified based on the nature of their electrolyte, which also determines their operating temperature, the type of fuel and a range of applications. Some of electrolyte types are acid, base, salt or a solid ceramic or polymeric membrane that conducts ions [6]. Table 10 summarizes the characteristics of various fuel cell types.

Unlike internal combustion engines and turbines, fuel cells demonstrate high efficiencies across most of their power range. This scalability makes fuel cells ideal for a variety of applications from the smallest to largest scale power generation. Yet, at present, fuel cells cannot compete with conventional energy conversion technologies in terms of cost and reliability [6].

Table 10
Summary of fuel cell types and their present characteristics.
Source: Edwards et al. [6].

Fuel cell type	Operating temperature (°C)	Applications	Electrical power range (kW)	Electrical efficiency (%)
Proton exchange membrane	60–110	Mobile, portable, low power generation	0.01–250	40–55
Alkaline	70–130	Space, military, mobile	0.1–50	50–70
Direct methanol	60–120	Portable, mobile	0.001–100	40
Phosphoric acid	175–210	Medium to large scale power and CHP	50–1000	40–45
Molten carbonate	550–650	Large scale power generation	200–100,000	50–60
Solid oxide	500–1000	Medium to large scale power and CHP, vehicle auxiliary power units, off-grid power and micro-CHP	0.5–2000	40–72

Comparatively, it makes no sense to introduce hydrogen in the transport sector without fuel cells, because of the high electricity to heat ratio and the high overall conversion efficiency of fuel cells in comparison to other power generation processes. For example, the efficiency of the fuel cell systems for passenger cars is over 40% compared to 25–30% for the gasoline/diesel powered internal combustion engines under real driving conditions [1]. Fuel cell systems have a higher efficiency at partial load than full load, which is very suitable for motor vehicles as they usually operate at part load during urban driving or even highway cruising. In addition, the fuel cells exhaust generates zero emissions when fueled by hydrogen. Road transportation noise in cities would also be appreciably reduced. Furthermore, fuel cell vehicles could even act as electricity generators when parked and connected to a supplemental fuel supply. Therefore, the use of hydrogen in internal combustion engines can only be a temporary solution.

Currently, power train expenses of fuel cell vehicles are still far from being cost-competitive. The greatest challenge for hydrogen use in the transport sector is the necessity to drastically reduce fuel cell costs from currently more than $2000/kW to less than $100/kW for passenger cars [1]. Yet, fuel cell drive systems offer totally new design opportunities for vehicles. They provide better design flexibility, fewer vehicle platforms and hence more efficient manufacturing approaches, since they have fewer mechanical and hydraulic subsystems compared with combustion engines. These design opportunities may consequently lead to additional cost reductions. However, this cost reduction potential has to be realized first and is important to the requirements for efficiency and lifespan. These requirements are the main source of uncertainty for the market success of fuel cell vehicles, as well as some technical challenges like hydrogen storage and safety issues.

5. Integrated hydrogen production systems

It is now suggested that coupling of nuclear and renewable energies is suitable to address the global climate change challenge. For a long time to come, nuclear energy will be serving as a support, make-up and back-up power suppliers in the transition to an almost complete renewable energy sector. This is shown in the left panel of Fig. 12. Half or more than half of the power is generated in nuclear base-load stations (full/constant load) and the other half (the variable loading) is covered by renewable energies.

The power generation must be from the flexible sources since the demand is irregular daily and seasonally, as shown in right panel of Fig. 12. In many markets usually the price of peak electricity is 3–4 times that of base-load electricity. The renewable plants will equal almost the peak capacity of the systems, and consist mainly of flexible technologies by which the production capacity can be controlled easily to ramp up and down. Renewable sources are available in a fluctuating and partly unpredictable way. Currently, the variable electric power output of most electrical grids is achieved by varying the power output of low-capital-cost, premium-fueled fossil power plants. For future electrical grids, however, meeting variable electrical demand economically becomes one of the main challenges since there are constraints on the use of fossil fuels. Therefore, nuclear and renewable coupled hydrogen systems are potential solutions to the challenge of producing peak energy and are also enabling technologies for the large-scale use of renewable energy options such as solar and wind. Without hydrogen, the contribution of renewable energy sources will be limited since there is no method to effectively (cost and efficiency wise) store electricity yet. A more practical approach would be the construction of nuclear power plants in serial running permanently at full load and directing extra capacity that the grid cannot absorb for hydrogen generation. As a hydrogen production method, the direct way of electrolysis is unlikely due to high infrastructure costs and low efficiencies. Also, obtaining hydrogen by current commercial thermochemical cycles requires high-temperature reactors. These considerations lead to the conclusion that a low temperature thermochemical cycle, such as Cu–Cl cycle, can be one of the great hydrogen production options to couple with renewable and nuclear energy sources. Some nuclear–renewable integrated hydrogen production systems are described in the following sections.

Fig. 13 shows a coupling of renewables with a nuclear reactor to produce hydrogen. One way to deliver a constant or any required load profile to the grid is to equip the nuclear and renewable power plants with an energy storage device, such as a regenerative fuel cell (a combination of a hydrogen production system and a fuel cell with hydrogen storage), as shown in Fig. 13. The power synchronization (conditioning) and controls unit has an extremely complex function in this configuration. It must direct power from the renewable and nuclear power plants to either the grid or the hydrogen production cycle, and switch to fuel cell power when there is not enough power from the nuclear power plant. The renewable fuel cell system is typically less costly than a battery bank for high power/long duration storage. Another option is to use nuclear/renewable-generated hydrogen as a fuel for home cooking and heating, and/or for a fuel cell or hydrogen combustion engine-powered vehicle. This option may be attractive for remote areas.

5.1. Nuclear independent solar-hydrogen production

Instead of connecting to the grid, a solar array may be connected to the Cu–Cl cycle to produce hydrogen, which then can be used in a variety of applications, as shown in Fig. 14.

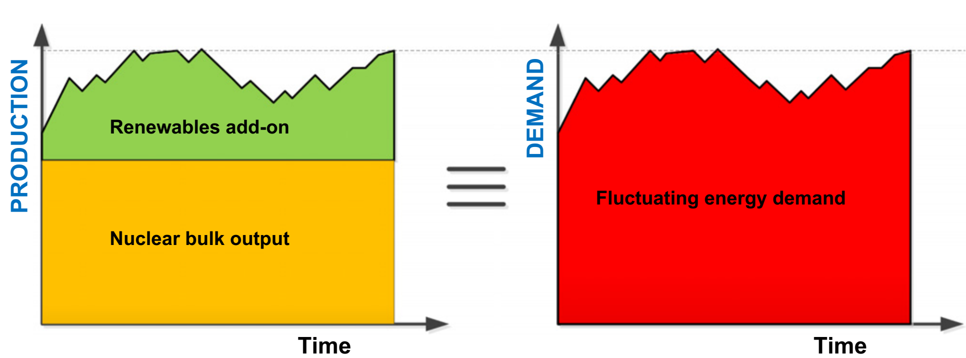

Fig. 12. Renewable energies add-on to nuclear bulk output versus the fluctuating energy demand.

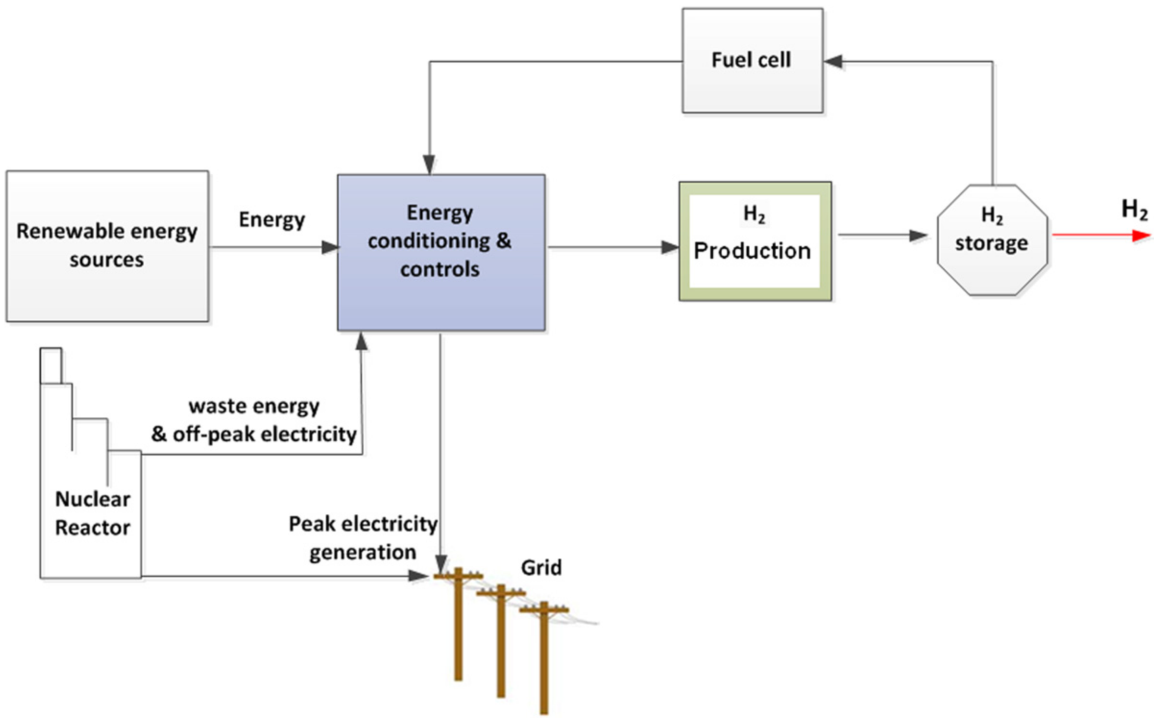

Fig. 13. Coupling nuclear and renewable energy sources in a smart grid.

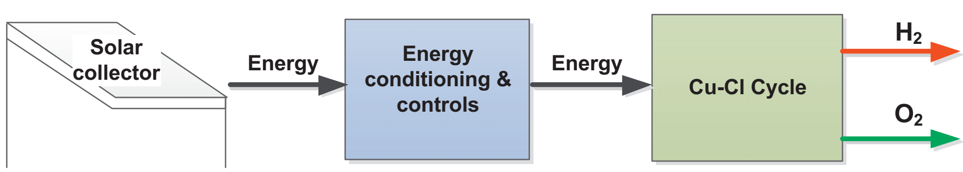

Fig. 14. Schematic diagram of nuclear independent solar-hydrogen generation.

If the solar installation is in remote and hence well isolated areas, grid may not be available at all. In that case delivery of hydrogen through a pipeline over a long distance may be an option. Some studies suggest that transmission of hydrogen through a pipeline in some cases may be more economical than transmission of electricity over a long distance [2].

The system in Fig. 14 has some drawbacks related to no backup energy source connection and generation imbalance charges. The Cu–Cl cycle will be exposed to the variable power supply, and a power regulator must be a part of the power conditioning and controls box in order to match the cycle's energy requirements at any power with minimum conversion losses.

Operation of a Cu–Cl cycle in combination with renewable energy sources, and particularly with a solar, has several specific issues. A Cu–Cl cycle may be sized to receive all the power generated from a solar, but it would operate with the same capacity factor as the solar plant, which is determined by the availability of solar energy. Capacity factor is a coefficient of utilization of installed capital, and therefore it is an important factor in determining the economics of any power generating and conversion device. A more economical option may be to size the Cu–Cl cycle at a power lower than the solar plant's maximum power output. In that case some of the power from the solar would be unutilized, but the Cu–Cl cycle would operate with a higher capacity factor. For any combination of solar availability and load profiles, there is an optimum Cu–Cl cycle capacity. Economics of solar-hydrogen systems is mainly related to the configuration of the system and its application, in addition to the available solar insolation. Direct coupling of a Cu–Cl cycle with a solar plant implies intermittent operation with highly variable power output.

5.2. Nuclear-assisted solar-hydrogen production

One way to eliminate problems with intermittent energy operation is to combine the solar with an input from the nuclear (Fig. 15), if available. The power conditioning/controls unit provides that the Cu–Cl cycle receives constant energy input, by combining the output from the solar with the required input from the nuclear. This way the Cu–Cl cycle may operate all the time at its design capacity. The capacity factor may reach 90% or higher (the only down-time would be for maintenance), which would significantly improve economics and reduce the cost of hydrogen.

5.3. Nuclear independent wind-hydrogen production

As discussed above hydrogen complements the renewable energy sources. An energy system that generates hydrogen from renewable sources is self-sufficient, clean, and represents a permanent energy solution for sustainable development. Wind power is a renewable option that, in some locations today, is cost competitive with conventional fossil fuel or nuclear generated electricity.

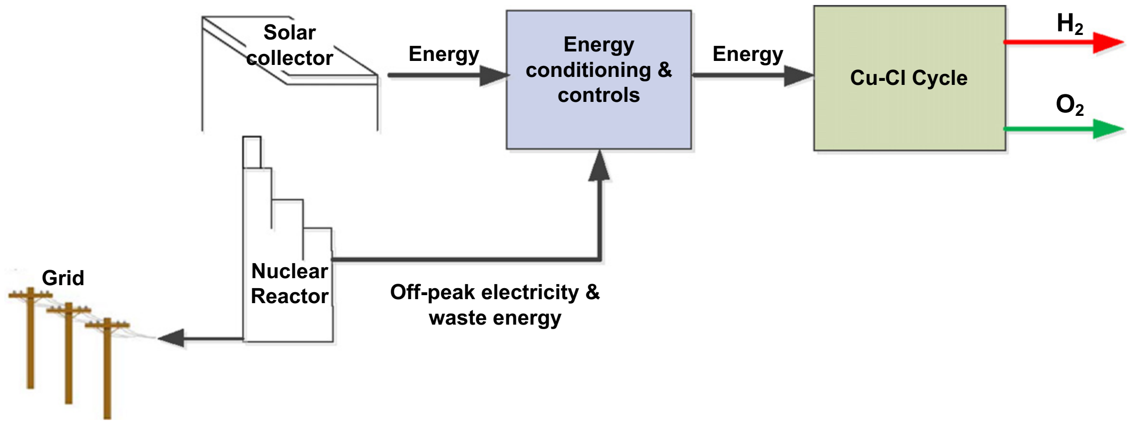

Fig. 15. Schematic diagram of nuclear-assisted solar-hydrogen generation.

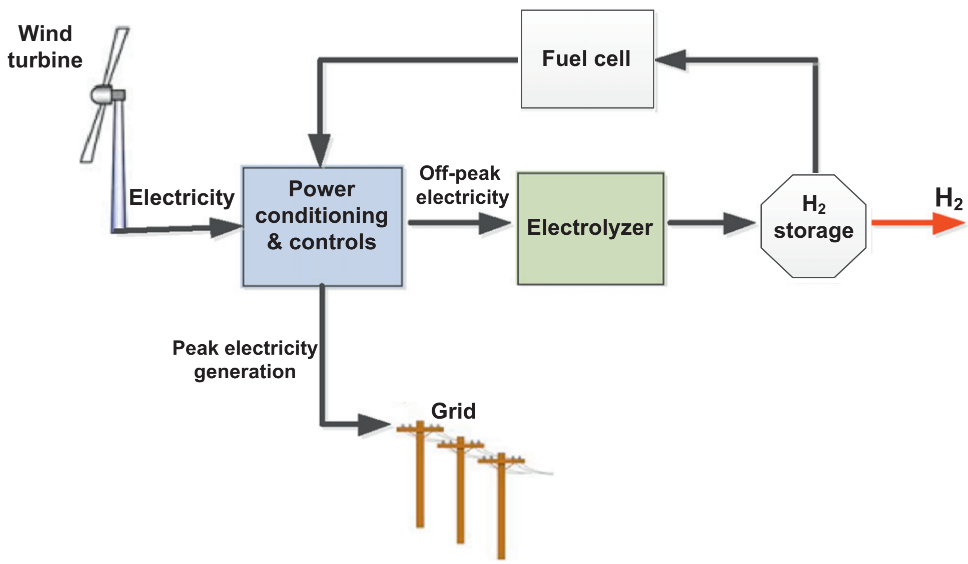

Fig. 16. Schematic diagram of nuclear independent wind-hydrogen generation.

Hydrogen can be produced from the wind-generated electricity for a variety of applications. It may be transmitted through pipelines to the users to utilize as a fuel directly. Also, it can be recycled in the system to enhance the performance of the wind turbine or a wind farm and match its output with the user expectations. Each of these applications is briefly discussed below. Wind power can be used to generate hydrogen in either nuclear-connected or stand-alone applications. The first option, as shown in Fig. 16, is to couple wind turbine with an electrolyzer to produce hydrogen since the Cu–Cl cycle is a hybrid cycle and cannot operate with only electrical power produced by the wind turbine.

One of the natural drawbacks of wind power is that the wind velocity is highly intermittent, changing with minutes, hours, days, and even seasons. It is commonly accepted that, although power from the wind turbine fluctuates significantly with time, the grid can readily absorb most of the wind power produced, as long as it is designed for less than 20% of the maximum load. Wind turbines operate with relatively low capacity factor because of a highly intermittent nature of its source. Wind power generation efficiency is around 35%. Wind power can impose some penalties when it cannot be called upon demand and scheduled energy is not delivered. These generation imbalance charges are costing wind plant operators around $0.10/kWh of undelivered energy [25]. Therefore, an electrolyzer may be sized to receive all the power generated from a wind turbine, but it would operate with the same capacity factor as the wind turbine. Capacity factor is a coefficient of utilization of installed capital and is an important factor in determining the economics of any power generating or energy conversion device. A more economical option may be to size the electrolyzer at a capacity lower than the wind turbine's maximum power output. In that case some of the power from the wind would be unutilized, but the electrolyzer would operate with a higher capacity factor. For any wind turbine availability and load profiles there is an optimum electrolyzer capacity. In addition to the availability of wind resources, economics of wind hydrogen systems greatly depends on the design of the system and its application.

This system may also incorporate a solar plant to couple with the Cu–Cl cycle (see Fig. 17), and also to add security and versatility to power supply. Combined wind and solar systems are in operation at the Desert Research Institute (Reno, Nevada), and at the Hydrogen Research Institute (HRI), at the Universite du Quebec, Trois-Rivieres [2]. These independently conceived systems use both solar and wind turbines to generate hydrogen. They use wind/solar to generate hydrogen at relatively small capacity, with a compressed hydrogen storage system.

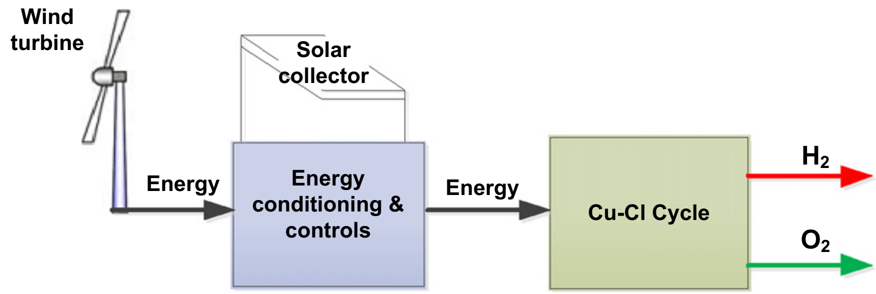

Fig. 17. Schematic diagram of nuclear independent wind-hydrogen generation with the Cu–Cl cycle.

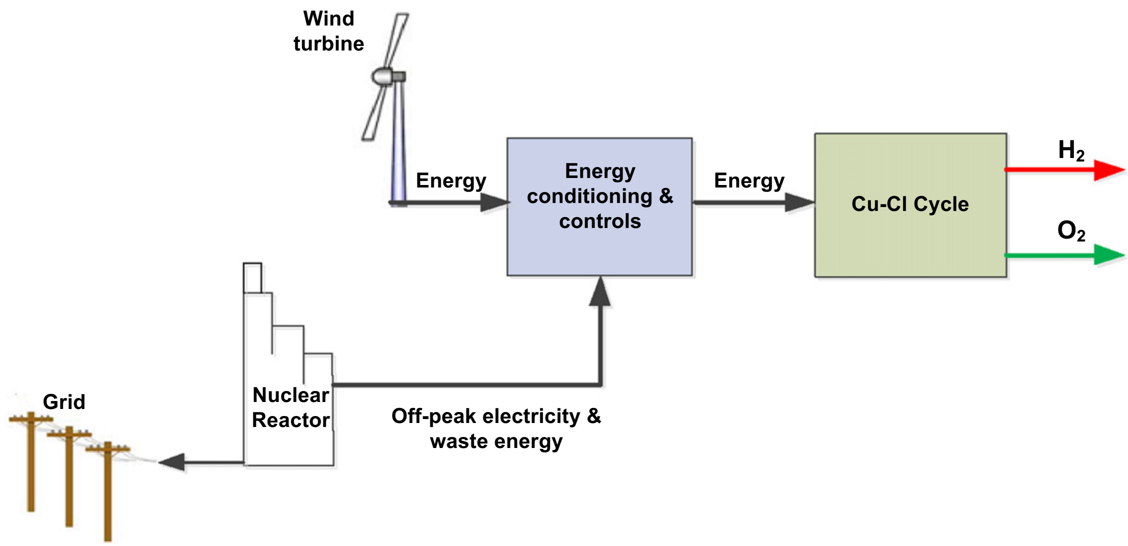

Fig. 18. Schematic diagram of nuclear-assisted wind-hydrogen generation.

5.4. Nuclear-assisted wind-hydrogen production

If nuclear is available, one way to eliminate problems with intermittent operation is to combine the wind turbine with an input from the nuclear reactor as shown in Fig. 18. The power conditioning/controls unit facilitates that the Cu–Cl cycle receives constant energy input by combining the output from the wind turbine with the required input from the nuclear reactor. And as a result, the Cu–Cl cycle can continually operate at its design/full capacity. The capacity factor may reach as high as 90%, in which the only down-time would be for maintenance. This combination of nuclear and wind powers would consequently improve the economics and reduce the cost of produced hydrogen.

5.5. Nuclear independent hydro-hydrogen production

Hydropower is a non-intermittent renewable energy source with a large scale production potential where it is available. The main challenge for hydropower is the gap between peak and off-peak electricity demand by end users. This problem remains unsolved and causes an enormous variation between peak and off-peak electricity cost since there is no cost- and energy-effective electricity storage technology available in the market yet. Thus, contribution of hydrogen with hydropower as an energy carrier can be a solution since it can be stored, transported and utilized very efficiently. In addition, it can be converted to any energy form when it is needed. Hydrogen may be produced from the hydro-generated electricity and utilized in a variety of applications. It can be stored, used as a fuel directly or transmitted through pipelines to the users. Hydropower can be used to generate hydrogen in either nuclear-connected or stand-alone applications. The first option, as shown in Fig. 19, is to couple hydro with an electrolyzer to produce hydrogen. The Cu–Cl cycle is not appropriate in this case since it is a hybrid cycle and requires heat input.

One way to deliver any required load at a constant rate to the grid is connecting the hydropower plant with an energy storage device, such as a regenerative fuel cell. Regenerative fuel cell, as shown in Fig. 19, is a combination of an electrolyzer and a fuel cell with hydrogen storage. The electrolyzer and fuel cell functions may be included in a single stack (unitized version) or in two separate stacks (discrete version). A compressor may be required to fill the hydrogen tank or the electrolyzer may be designed at high pressures. The power conditioning and controls unit have a very complex function in this configuration. It must direct power from the hydropower plant to either the grid or the electrolyzer. It also needs to switch the system to fuel cell power when there is not enough power from the hydropower plant. Furthermore, it provides voltage regulation, both from AC/DC (for the electrolyzer) and DC/DC (from fuel cell to grid). This renewable fuel cell system is typically less costly than a battery bank for high power/long duration storage. Another utilization option is to use hydro-generated hydrogen as a fuel for cooking and heating in the house and/or for a fuel cell or hydrogen combustion engine-powered vehicle. This option is attractive in remote locations where fuel delivery is not regular. This system may also incorporate a solar system, in available areas, to be able to couple with the Cu–Cl cycle as shown in Fig. 20.

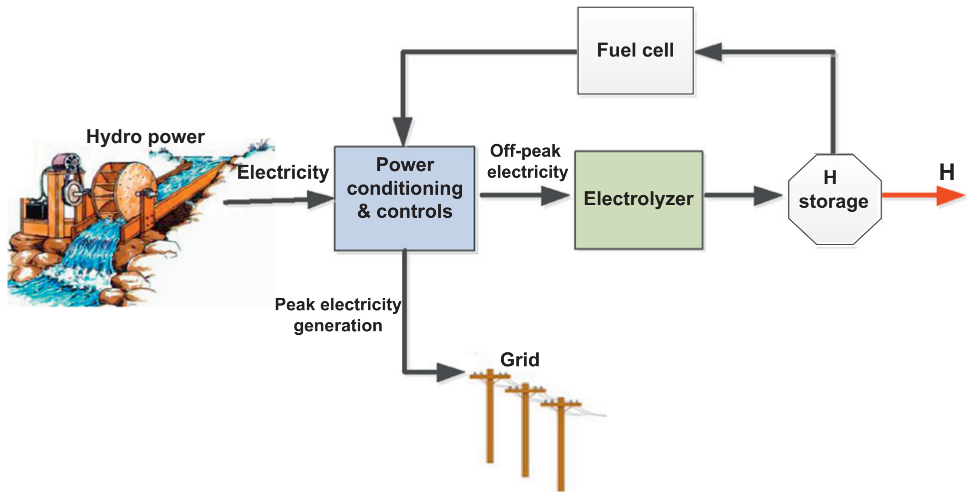

Fig. 19. Schematic diagram of nuclear independent integrated hydro-hydrogen energy system.

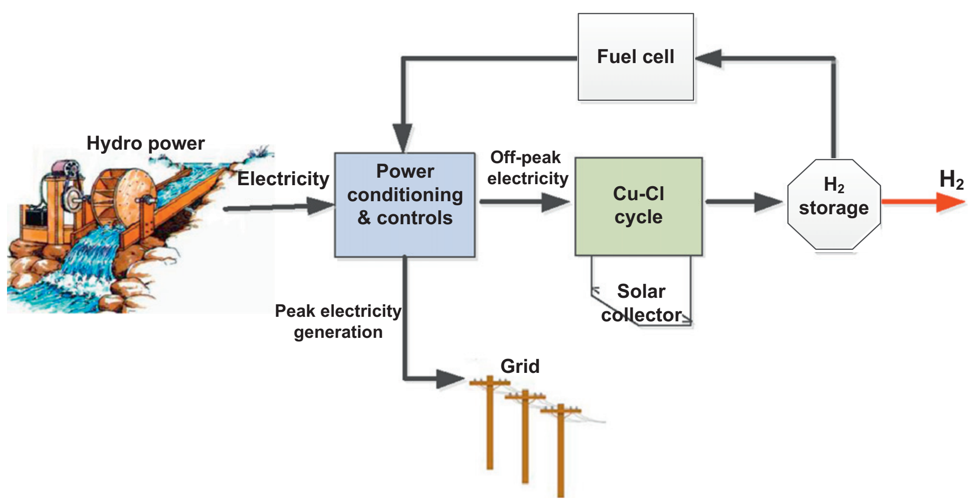

Fig. 20. Schematic diagram of integrated hydro-solar energy system for hydrogen production with the Cu–Cl cycle.

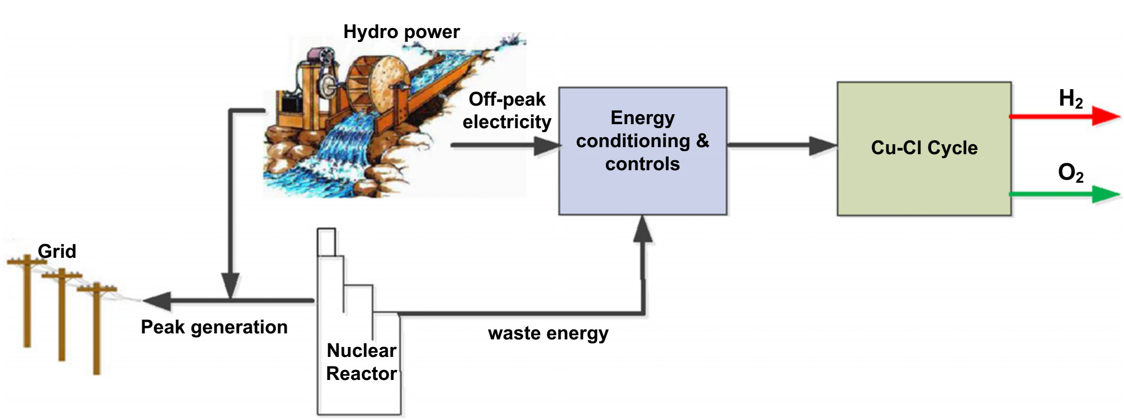

Fig. 21. Schematic diagram of nuclear assisted hydro-hydrogen production with the Cu–Cl cycle.

5.6. Nuclear-assisted hydro-hydrogen production

To eliminate problems with availability of heat when producing hydrogen by the Cu–Cl cycle, the hydropower plant can be combined with an input from the nuclear reactor (if available), as illustrated in Fig. 21. The power conditioning/controls unit facilitates that the Cu–Cl cycle receives constant energy input by combining the off-peak electricity from the hydropower plant with the required heat input from the nuclear reactor (preferably waste heat), so that the Cu–Cl cycle may operate continually

at its design level/capacity. Using off-peak electricity from the hydropower plant and waste heat from the nuclear reactor would significantly improve the economics and as a result the production cost of hydrogen is reduced. Full load electricity generation in the hydropower plant and nuclear reactor could be transferred directly to the grid during the peak demand.

5.7. Nuclear independent geothermal-hydrogen production

Another renewable-based hydrogen production option is using geothermal energy resources at their availability. The produced hydrogen, then, can be used as a fuel directly or transmitted through pipelines to the users. It can also be recycled in the power generation system to enhance the performance of the geothermal and match its output with the user expectations. In cases where the geothermal energy source is located in a remote area delivery of hydrogen over a long distance is generally a better option than transferring electricity. In general, storage and transmission of hydrogen through a pipeline is more economical than other energy carrier options.

As shown in Fig. 22, a geothermal source can be connected to a Cu–Cl cycle to produce hydrogen, which then may be used in a variety of applications as discussed above. As geothermal sources generally have low temperature drawback, the Cu–Cl cycle is therefore very convenient hydrogen production option to couple with the geothermal since it has a lower operating temperature compared to other hydrogen production technologies. The system shown in Fig. 22 can also be coupled with a solar PV array or a wind turbine (whichever is available in the area) to compensate the small (compared to heat requirement) electricity need of the hybrid Cu–Cl cycle.

Other configurations for using geothermal energy for hydrogen production and liquefaction are also proposed. Kanoglu et al. [13] developed four models for the use of geothermal energy for hydrogen production. These models are illustrated in Fig. 23. The first model uses geothermal work output as the work input for an electrolysis process (Fig. 23a). The second model uses part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water (Fig. 23b). In the third model, geothermal heat is used to preheat water in a high-temperature electrolysis

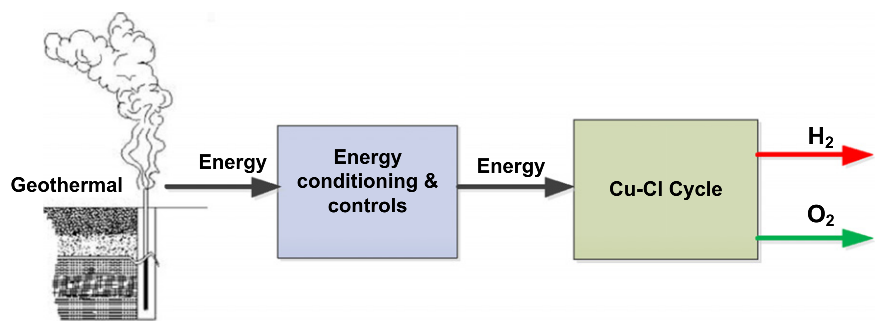

Fig. 22. Nuclear independent geothermal-hydrogen production system.

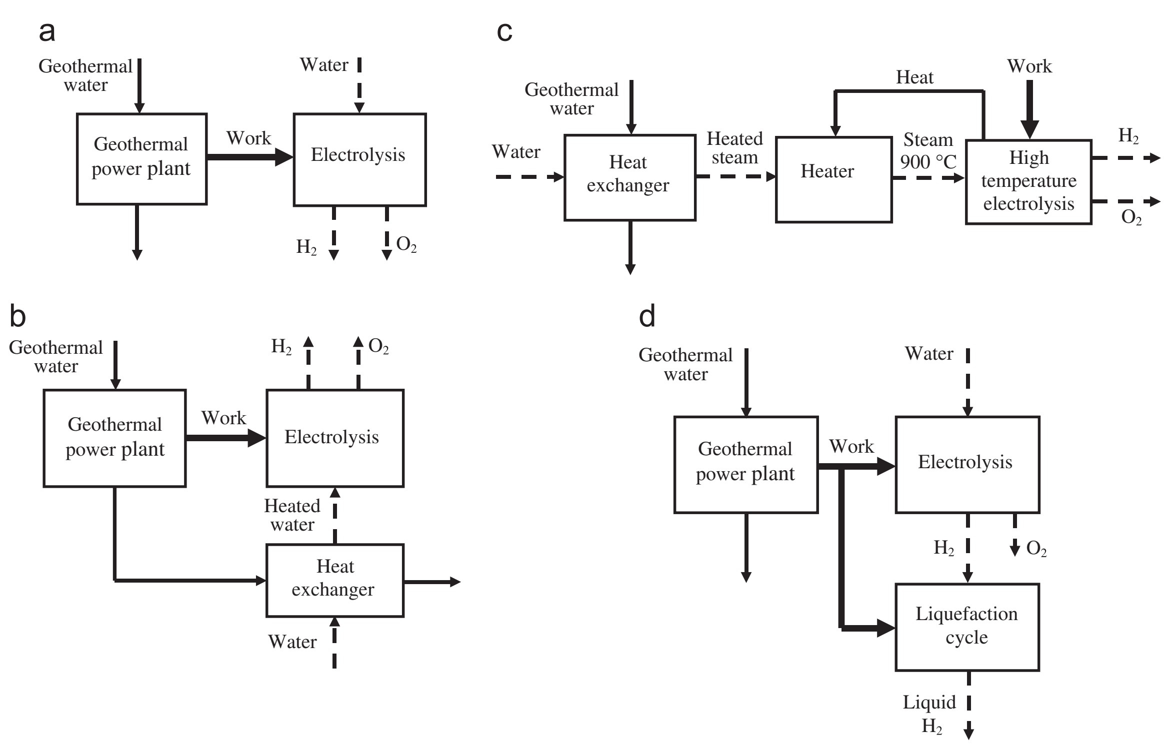

Fig. 23. Four models considered in the hydrogen production with electrolysis: (a) using geothermal work output as the input for an electrolysis process. (b) Using part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water. (c) Using geothermal heat to preheat water in a high-temperature electrolysis process. (d) Using part of geothermal work for electrolysis and the remaining part for liquefaction [13].

process (Fig. 23c), while in the fourth model, part of geothermal work is used for electrolysis and the remaining part for hydrogen liquefaction (Fig. 23d).

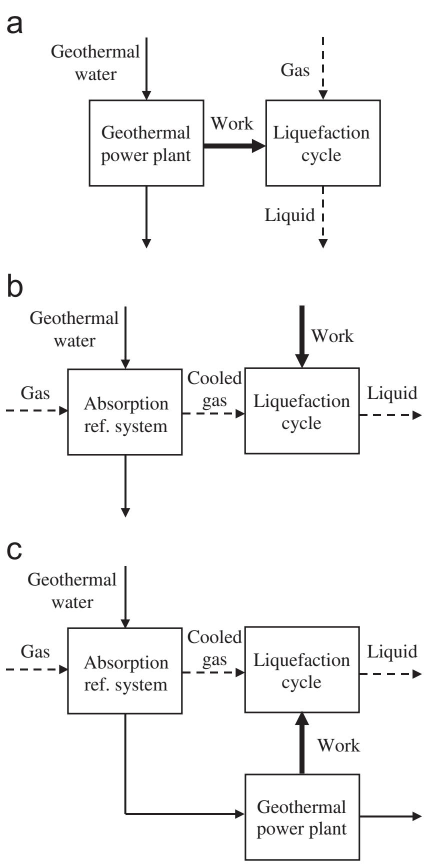

Fig. 24. Three cases considered in the analysis. (a) Work output from a geothermal power plant is used as the work input for a liquefaction cycle. (b) Geothermal water provides heat to the absorption refrigeration system (ARS) and hydrogen gas is cooled in the ARS and liquefied in the liquefaction cycle. (c) Geothermal water provides heat to the ARS and then is used to generate work in a power plant, while hydrogen gas is cooled in ARS and then liquefied in the liquefaction cycle [14].

An investigation of these geothermal assisted hydrogen production models indicates that as the temperature of geothermal water increases the amount of hydrogen production increases. Greater amounts of hydrogen may be produced in Model 3 compared to other models. Model 2 performs better than Model 1 because of the enhanced use of geothermal resource in the process. Model 4 allows both hydrogen production and liquefaction using the same geothermal resource, and provides a good solution for the remote geothermal resources [13].

Kanoglu et al. [14] proposed the use of geothermal energy for hydrogen liquefaction, and investigated three possible cases, as shown in Fig. 24. These cases include (1) using geothermal power as the input for a liquefaction cycle (Fig. 24a), (2) using geothermal heat in an absorption refrigeration process to precool hydrogen gas before it enters a liquefaction cycle (Fig. 24b), and (3) using part of the geothermal heat for absorption refrigeration to precool the gas and part of geothermal heat to produce power for use in the liquefaction cycle (Fig. 24c).

5.8. Nuclear-assisted geothermal-hydrogen production

The geothermal-hydrogen production system can also be combined with nuclear, if available; this way the electricity requirement of the Cu–Cl cycle may be maintained. This configuration is illustrated in Fig. 25. The power conditioning/controls unit facilitates that the Cu–Cl cycle receives constant energy input by combining the output heat from the geothermal with the required input electricity from the nuclear. This way the Cu–Cl cycle can operate at its design level/capacity continuously. Based on the capacity of the geothermal source, off-peak electricity and waste heat from the nuclear reactor could be used to reduce the cost.

5.9. Nuclear independent biomass-hydrogen production

Biomass is one of the renewable sources that, in some locations today, presents a competitive energy option. In areas where biomass is available, hydrogen can be produced to store and carry the available energy. The produced hydrogen could be used as a fuel directly, or transmitted through pipelines to the users. If the biomass source is in a remote area delivery of hydrogen over

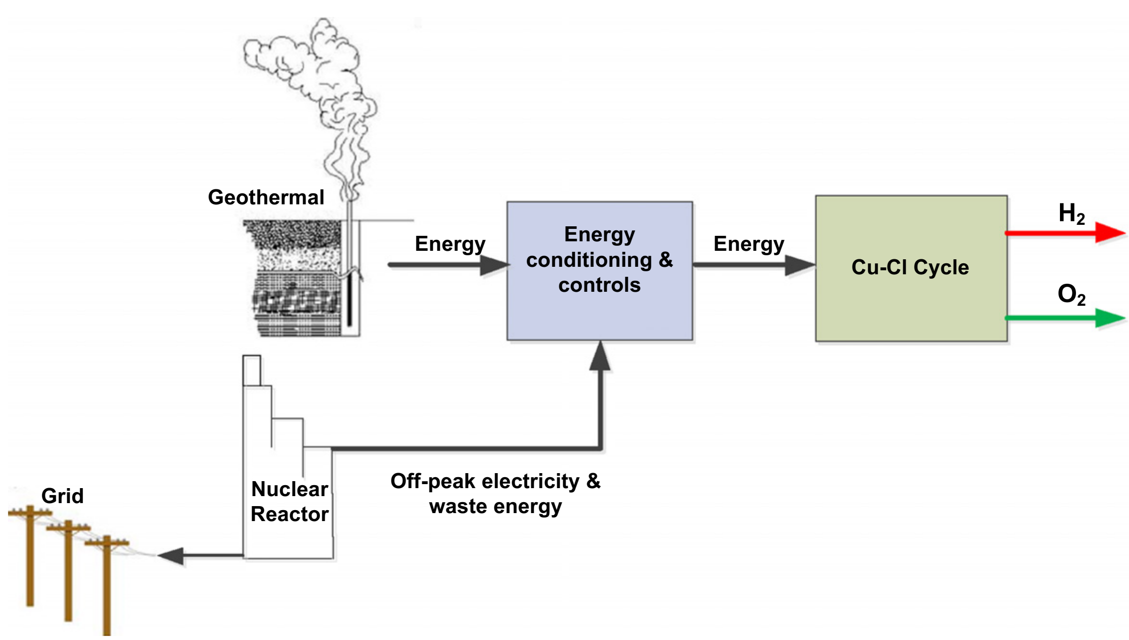

Fig. 25. Nuclear assisted geothermal-hydrogen production with the Cu–Cl cycle.

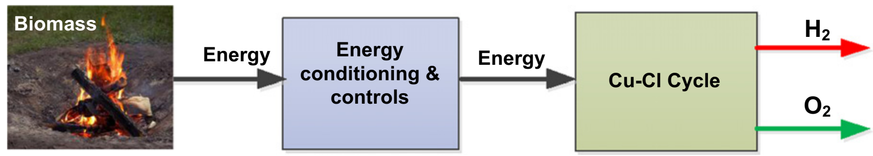

Fig. 26. Nuclear independent geothermal-hydrogen production system.

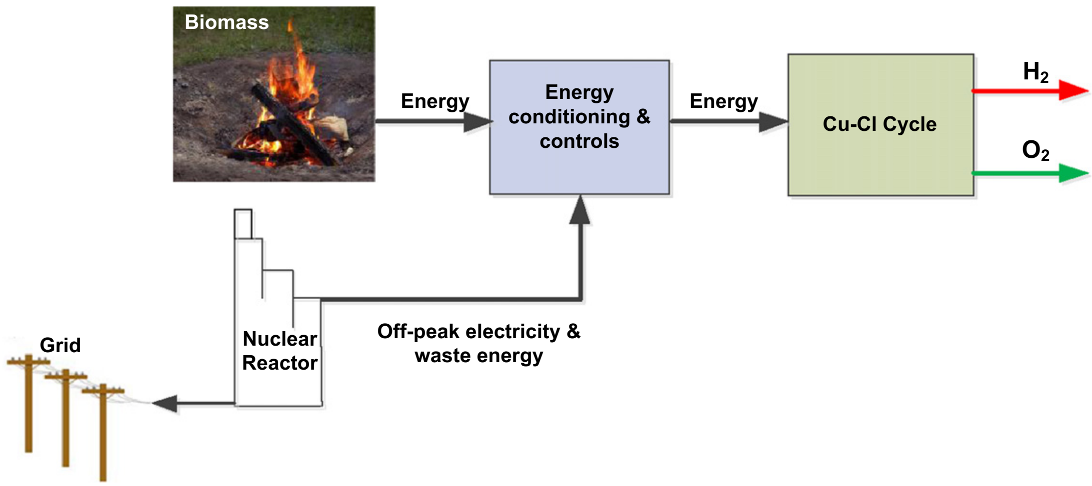

Fig. 27. Nuclear assisted biomass-hydrogen production with the Cu–Cl cycle.

a long distance may be a better option. A biomass powered hydrogen production system is given in Fig. 26. In the figure, a biomass energy source has been connected to a Cu–Cl cycle to produce hydrogen, which then can be used in a variety of applications. This system can also be coupled with a solar PV array or a wind turbine (whichever is available in the area) to compensate the small (compared to heat requirement) electricity need of the hybrid Cu–Cl cycle.

5.10. Nuclear-assisted biomass-hydrogen production

The above given biomass-hydrogen production system could also be combined with nuclear, if available; so that the electricity requirement of the Cu–Cl cycle can be provided. This configuration is illustrated in Fig. 27. The power conditioning/controls unit facilitates that the Cu–Cl cycle receives constant energy input, by combining the output heat from the biomass with the required input electricity from the nuclear. Based on the capacity of the biomass source, off-peak electricity and waste heat from the nuclear reactor could be used to reduce the cost of produced hydrogen.

6. Conclusions

This paper is a brief summary of the state of current energy resources and use, and of possible paths to the future, including hydrogen, and nuclear and renewable energies. It explores global energy demand, and hydrogen's role, over the 21st century. Based on extensive research interviews, supplemented with a review of the academic literature, this article assesses the best way to promote renewable energies using nuclear as a back-up/supplementary option and hydrogen as an energy carrier.

The traditional paradigm is that nuclear, fossil, and renewable energy sources are competitors. Today we face two sustainable energy challenges: the need to avoid global climate change and the need to replace traditional crude oil as the basis of our transport system. To address these challenges, radical changes in our energy system will be required. This requires rethinking the roles of different energy sources and considering energy systems that tightly couple nuclear and renewable energy sources to create nuclear–renewable systems. The pathway to such a future will likely be initiated in the production of gas/liquid fuels (energy carriers) such as hydrogen to enable efficient and cheap energy storage and transportation. Nuclear–renewable future involve nuclear plants providing heat—a product for which the nuclear economics in many cases are economically competitive today and where the initial nuclear–renewable hydrogen options require no new technology. In the longer term, nuclear energy is potentially the enabling technology for the large-scale use of renewable energy because nuclear energy may be able to provide peak energy when the sun does not shine or the wind does not blow and the other renewables are not available. The integration of renewable and nuclear energies for the production of hydrogen can prove to be a sound path for a sustainable energy future.

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